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GENERIC MODELING OF A LIFE SUPPORT SYSTEM FOR PROCESS TECHNOLOGY COMPARISONS

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ABSTRACT

A generic model of a physical-chemical life support system has been developed by the Jet Propulsion Laboratory for the National Aeronautics and Space Administration (NASA) to quantitatively compare and select system and technology options for long-duration manned missions. The model consists of a modular, hierarchical break down of the life support system into subsystems, and subsystems into subsystem functional elements representing individual processes. The simulation model is called the Life Support Systems Analysis Simulation Tool (LiSSA-ST) .

This paper describes the Generic Modular Flow Schematic (GMFS) modeling technique. The GMFS can be used to synthesize, model, analyze, and quantitatively compare many configurations from simple, open-loop to complex closed-loop life support systems. The GMFS is coded in ASPEN Plus to compute the material and energy balances on a steady-state person-day basis. Selected output is stored in a file for subsequent importing to a spreadsheet program where important parameters including weight, power, and volume of the life support system are computed. The spreadsheet program is called the Life Support Systems Analysis Trade Tool (LiSSA-TT) .

Results of using the LiSSA-ST and the LiSSA-TT will be presented for comparing life support system and process technology options for a Lunar Base with a crew size of 4 and mission lengths of 90 and 600 days. System configurations to minimize the life support system weight and power are explored.

INTRODUCTION

The potential complexity of future life support systems for manned missions necessitates the development of the appropriate systems analysis capability within NASA as a guide to technology and systems development (Evanich et al, 1991) . The life support system (LSS) most appropriate for a given manned exploration of outer space must be chosen from candidates ranging from a very simple, non-regenerative LSS to a very complex, integrated biological and physical-chemical closed loop LSS. There are many regenerative processes that are potential candidates to provide a particular function as part of the overall LSS. To synthesize an LSS, all of the processes must be integrated to perform certain generic life support functions such as air revitalization and water recovery.

A GMFS architecture has been developed to enable synthesis, analysis, and eventual selection of system and technology options for defined missions. The architecture consists of a modular, top-down hierarchical break-down of the physical-chemical closed loop life support (P/C CLLS) system into subsystems, and further break-down of subsystems into subsystem functional elements (SFEs) representing individual processing technologies. This approach allows for modular substitution of technologies and subsystems and for the traceability of parameters through all the hierarchical levels which is useful in comparing systems or technologies rapidly and accurately. The GMFS is the central feature utilized by the Life Support Systems Analysis (LiSSA) tool created by JPL as illustrated in Figure 1..

A series of papers titled "Human Life Support During Inter-planetary Travel and Domicile" have been presented at recent International Conference on Environmental Systems (ICES) meetings that describe the technique and results. It should be noted that the acronym LiSSA was adopted in early 1992 and therefore will not be found in earlier papers.

Part I, titled "System Approach", was presented at the 1989 ICES Conference (Seshan et al., 1989). It discussed the need to resolve issues stemming from widely differing system parameter estimates for the same system. It was argued that a top-down functional break-up of the system followed by a bottom-up allocation of technologies and other resources would considerably facilitate LSS modeling. By making a carefully orchestrated system approach to life support, the cost of developing life support technologies could be objectively managed.

Part II of the series, titled 'Generic Modular Flow Schematic Modeling", was presented at the 1991 ICES conference (Ferrall et al., 1991). The Generic Modular Flow Schematic (GMFS) architecture was described to be capable of encompassing all functional elements of a P/C CLLS system. The GMFS concept was found to be extremely useful in synthesizing, modeling, analyzing, and quantitatively comparing complex closed loop and partially closed loop configurations. A baseline set of technologies being considered for Space Station Freedom was chosen to perform system analysis for a Mars Expedition mission.

Part III (Seshan et al., 1991) presented a system trade study for a Mars Expedition Mission comparing open and closed loop systems. A crew size of 3 was used with a total mission duration of 440 days; this included a stay of 30 days at Mars where a lander vehicle would transport two astronauts to the surface (Craig and Lovelace, 1989). Hence, two separate life support systems are needed: one for the orbiter (or transfer vehicle) and one for the lander for this Mars mission. Three systems were modeled: a totally open loop system, a carbon dioxide removal system, and a closed loop system. The totally open loop system has no waste processing; hence, all material entering as feed exit as trash. The carbon dioxide removal system processes the cabin air to remove carbon dioxide and requires supplies of oxygen and water. The closed loop system regenerates all of the oxygen required and greater than 90% of the water required. Total system weight comparisons showed the open loop systems to be non-competitive with respect to weight for either the long duration orbiter or short duration lander vehicles. By analyzing the closed loop system for both the orbiter and lander, it was observed that for longer duration missions, storage dominates the weight of the system, while for shorter durations, the processing equipment becomes more significant.

Part IV was presented at the 21st ICES conference (Rohatgi et al., 1991a). It described results of trading processing technologies in a closed loop configuration for a Mars Expedition Mission. Technologies were traded and compared to a baseline set for the following functional elements: Carbon Dioxide Removal, Carbon Dioxide Reduction, Oxygen Generation, Potable Water Recovery, Hygiene Water Recovery, and Urine Processing. Several of the technologies traded are considerably less developed than their corresponding baseline technology. Hence, weight or power advantages of a less-developed technology over a more-developed technology must be seen only as a potential advantage. LSS weight saving potentials for the long duration Mars mission could be realized from the multifiltration (MF) water recovery technology and certain combinations of advanced carbon reactor system (ACRS), carbon dioxide electrolysis/ Boudouard (CO_2EL/BD), water vapor electrolysis (WVE), two-bed molecular sieve (2BMS), and air polarized concentrator (APC) technologies for oxygen regeneration. LSS power saving potentials for the long duration Mars mission could be realized by the APC, 2BMS, and CO_2EL/BD technologies for oxygen regeneration. For water recovery, a small advantage could be realized by the use of MF and WVE technologies. For short duration missions, the non-regenerative LiOH was found to be more advantageous compared to oxygen regeneration technologies.

Part V, presented at the 1993 ICES conference (Ferrall et al., 1993), described potential benefits of including solids waste treatment in a LSS for the Mars mission. SWT technologies compared were freeze drying, thermal drying, incineration, wet oxidation, and super-critical water oxidation. The use of solid waste treatment was found to impose weight and power penalties to the P/C LSS that is traded for the potential benefit of reducing the mass of hazardous liquid and solid wastes.

Another paper presented at the 21st ICES conference described hardware scaleup procedures used in the LiSSA trade tool (Rohatgi et al., 1991) .

This paper will present the following:

1. LiSSA approach and calculation scheme
2. Description of the GMFS architecture
3. ASPEN coding of the GMFS modules
4. Metabolic and Hygiene Load Basis
5. Physical/Chemical Life Support Technologies
6. Life Support System Technology Trade Results
7. System Configurations to Minimize Power
8. System Configurations to Minimize Weight
9. Conclusions .

LiSSA APPROACH AND CALCULATION SCHEME

A schematic of the LiSSA methodology is given in Figure 1. To initiate the analysis, the System Matrix, Technology Matrix, System Specifications, and Mission Specifications are first chosen.

The system matrix includes the types of life-support systems that are of interest. It could include non-waste-processing open loop systems, systems that process cabin air for carbon dioxide removal only, and closed loop systems with varying degrees of closure of the oxygen and water loops. 'Closing the loops for oxygen and water is accomplished by processes which regenerate pure oxygen and clean water from waste streams generated by the *crew.* The amounts of oxygen and water regenerated depend on the efficiency of the regeneration processes selected for the system.

The technology matrix includes the processing technologies that would be utilized to regenerate oxygen and water. From this *matrix,* a baseline set of technologies can be chosen for is

configuring the various systems in the system matrix. Currently, the includes technologies under consideration for Space Station Freedom (SSF) and some additional advanced technologies,

System specifications include metabolic and hygiene inputs and outputs pertaining to the crew. These specifications are required as input parameters to the GMFS module integration and computer simulation. Mission specifications are required as parametric inputs to the LiSSA Trade Tool .

For all the technology candidates considered, performance data must be acquired and utilized to model technologies as modules using the ASPEN Plus chemical. process simulation package. Once all the ASPEN Plus modules are written, they are stored in an insert library. The modules are integrated into the GMFS architecture by calling them from the library using insert statements in the ASPEN input file. The complete input-code package represents the LiSSA Simulation Tool to produce output as an American Standard Code For Information Interchange (ASCII) file (with the *.PRN extension) that is used as input to the LiSSA Trade Tool.

The link between the LiSSA ~~Simulation~~ Tool and the LiSSA Trade Tool is accomplished by a Lotus 1-2-3 macro which processes and loads the ASCII file from the simulation output into the Trade Tool .

do we need copyright symbol for Lotus or could we replace this with another nomenclature such as "commercially available spreadsheet software"

The Trade Tool uses simulation output, mission specifications, and JPL-developed scaleup formulas for weight, power, and volume.

The entire spreadsheet represents the systems analysis output with a variety of tables and graphs.

GMFS ARCHITECTURE

The GMFS architecture can be described in terms of the following hierarchical levels:

Level O: This level describes the overall P/C CLLS and its interfaces with the spacecraft (S/C) or planetary base; a description of Level O would include weight and volume of the entire system and heat and material flows between the system and the spacecraft/base. A Level O GMFS is illustrated in Figure 2-A. The S/C provides supplies and utilities including heating demand, cooling demand, and power. Trash is defined as any material output from any SFE that will not be processed for recovery of needed materials; e.g. , plastic bags. Trash can either be directly stored for the mission duration or disposed overboard. Waste is defined as any material output from any SFE that can be processed to recover a necessary life support material . For example, condensate from cabin air is a waste stream which could be cleaned up to recover potable water.

Level I: This level breaks the P/C CLLS down into subsystems such as storage, temperature and humidity control, air revitalization, etc. ; a description of Level I would include weights and volumes of each subsystem and corresponding heat and material flows to and from each subsystem. Level I is illustrated by Figure 2-B. All of the material streams are shown as generically coming from either a fresh, waste, or trash stream "bus". This is shown as a simple representation of a large number of streams that the GMFS architecture requires. A more detailed GMFS has been documented (Ferrall et al. ,1989) which breaks down the fresh, waste, and trash streams further. Subsystems shown include Storage, Human Habitat, Temperature and Humidity Control, Air Revitalization, Water Management, Solid Waste Treatment, Master Computer Control and Major Monitoring Instrumentation, and Trash Disposal..

Level II: This level breaks the subsystems down into SFES; each functional element is generic, such that regardless of subsystem or technology choice, the identity of the functional element is maintained. A description of Level II would include weights and volumes of each subsystem functional element, plus corresponding heat and material flows to and from each subsystem functional element. Level II is illustrated in Figure 2-C. No streams are shown here so as not to burden the reader with too much detail. nomenclature However, the subsystems are shown with their constituent SFES as a 2-digit alpha-numeric. The subsystems and their respective SFE descriptions are given in Tables 1-A through l-H.

Level 111: This level expresses the subsystem functional element in terms of actual hardware equipment (or components) . This level is considered non-generic since a functional element could be implemented in different ways by ~~different~~ various pieces of hardware. A description of Level III would include an equipment list with corresponding weights, volumes, and heat and material flows to and from each listed equipment item. Modeling of Level III can be done either to simulate each major piece of equipment or to simulate the functional performance of the SFE. A Level 111 GMFS is illustrated in Figure 2-D, which shows a schematic of SFE #46. The details are specific to the reverse osmosis (RO) / multifiltration (MF) technologies. This SFE performs the function of removing dissolved solids by RO and other impurities to produce a hygiene quality water. In addition to the RO technology which performs the primary SFE function of removing dissolved solids, other technologies that support this function are represented in the diagram. They include a particulate filter/heater which kills and filters bacteria, an ultra-filtration module to remove solids that would plug the RO membrane, and MF unibeds to remove other contaminants by sorption and ion exchange which are not removed by RO. The input and output streams to the SFE for material, thermal, and power can and do interface with other SFEs within the LSS via a flow 'bus". This feature is illustrated in Figure 2-D for the cleanup, production and distribution of hygiene water. As stream S46E1 is an output of SFE #46 which joins the stream "bus" to be combined with other hygiene water streams from SFES 41, 44, 45, 46, and 47 of the Water Management Subsystem as illustrated in Figure 3-A. The output of the total subsystem is stream SR4E. Hygiene water return streams from different subsystems are likewise combined in the bus as given in Figure 3-B, (streams SR4E and SR2E are combined to form the total system hygiene water flow as stream SRE) . This stream now constitutes the entire regenerated return flow to hygiene water storage. A supply bus, also illustrated in Figure 3-B, shows the distribution of the system hygiene water flow (stream SSE) to the Human Habitat and Air Revitalization Subsystems as streams SISE and S3SE, respectively. The GMFS architecture as shown here is designed to be modular. An SFE block is structured with a preset number of identified material and energy streams entering or leaving the block. For example, SFE #46, as shown above, contains preset, well-defined connections, or nodes. Not all of the connections need to be utilized for a given SFE technology or hardware package. A different process could perform the same function with a different subset of the potential connections provided for in the generic module. This modular design facilitates the task of rapidly reconfiguring an LSS with substitute technologies by plugging/unplugging different Level III SFE modules. This modular design extends upwards to Level I blocks, or subsystems, which also come with preset connections as shown in Figure 3-A for the water management subsystem.

ASPEN CODING OF THE GMFS MODULES

Once the GMFS architecture has been set, modeling of individual SFEs can be initiated. Since the **GMFS is** modular in design, an existing SFE model could be substituted by a different model as long as the unused but predefined material stream, power, and heat flow interfaces are given a nonzero value. Referring to Figure 2-D, SFE 46 could be substituted by another technology that would perform the same function of Hygiene Water Processing as long as the inputs and outputs, or "hooks' to the SFE, are accounted for. If there is no actual flow associated with a hook , an insignificantly small quantity is assigned to it. Each modeled SFE is called a "flowsheet" within ASPEN. ASPEN handles each SFE flowsheet separately and calculates overall heat and material balances for each flowsheet.

An example of an ASPEN flowsheet is shown in Figure 4, which simulates CO_2 Reduction(SFE #34) . The associated schematic shows a Level III representation of the GMFS with hooks for the SFE illustrated as inputs and outputs. In addition, ASPEN blocks and streams are shown. The model shows the feed stream, S34Q1, mixing with a recycle stream, then being subsequently compressed, mixed with a hydrogen feed stream S3401 , heated, reacted, and the resulting solid carbon separated as stream S34007. The consumption of chemicals, which for the Bosch technology is a canister, is represented by Stream S34I1. Cooling demand is represented by heat removed as CD(3,4) , and power is represented by PWR(3,4), which includes power for a compressor, a gas/liquid separator, and the reactor. Heat loss is picked up by the circulating air, S34KI. Solid carbon is separated and combined with the canister to become S34Y1.

The modular nature of the GMFS allows for modeling Level III technologies to different levels of detail. In some models, FORTRAN input blocks are used to calculate parameters such as power and heat loss as functions of another parameter, such as CO_2 feed rate. In this way, the process modeling can be simplified for each SFE to minimize the computational load while maintaining the level of detail necessary for systems analysis.

After several SFES are modeled, the subsystem is integrated by combining similar SFE connections to generate subsystem connections. The order of SFE calculations within the model is handled explicitly by defining a sequence for each SFE and then giving a sequence of these sequence blocks. For example, calculations for the Air Revitalization Subsystem can be specified to proceed according to the ollowing sequence:

```
(SEQUENCE SEQ31)   (SEQUENCE SEQ33
(SEQUENCE SEQ34)   (SEQUENCE SEQ35
(SEQUENCE SEQ37)   (SEQUENCE SEQ38
```

Once all the subsystems have been modeled, the overall sequence is given including convergence specifications and custom FORTRAN blocks . For the GMFS, a **FORTRAN** block at the very start of the program is used to input various parameters, such as metabolic quantities, percent of regeneration desired, and CO_2 partial pressure in the circulating air, etc. To extract pertinent output for further systems analysis in a spreadsheet, an ASCII file is created by a FORTRAN block. Data extracted into this file includes values that characterize the SFE, including ‘hook” values and other parameters necessary to calculate the weight and volume of each individual SFE. Power, heating, and cooling demands for each SFE are calculated within ASPEN and also printed in this file. Summed stream values for each subsystem, and total P/C CLLS system values can also be included.

METABOLIC AND HYGIENE LOAD BASIS

A metabolic mass balance has been established and is presented in Table 2. This balance is the result of combining several literature sources into a consistent elemental balance that is sufficiently detailed to perform systems analysis using the LiSSA-ST with ASPEN Plus.

Space Station Freedom (Marshall Space Flight Center, 1991) has established nominal mass values for the following:

METABOLIC INPUTS	METABOLIC OUTPUTS
Dry food	Cc)*
Water in food	Urine H_2O
Drinking water	Urine Solids
Consumed oxygen	Feces H_2O
	Feces solids
	Respiration & Perspiration H_2O
	Sweat solids

In addition, there is also a nominal value specified for the metabolic heat release rate.

However, the elemental compositions of the waste solids are not stipulated. If chemical processing and transformation (e.g., oxidation of feces and urine wastes) are to be performed, this information must be known. Investigators at NASA's Ames Research Center (Wydeven and Golub, 1990 and Golub and Wydeven, 1992) have collected chemical compositions of various human waste streams including trace compounds. However, the data collected is not correlated to the composition of food ingested by the human crew. Others (Volk and Rummel, 1986) have illustrated mass balances between metabolic inputs and outputs by establishing representative chemical formulas for food and waste streams as follows:

Food protein	C_4H_5ON
Food carbohydrate	$C_6H_{12}O_6$
Food fat	$C_{16}H_{32}O_2$
Urine solids	$C_2H_6O_2N_2$
Feces solids	$C_{42}H_{69}O_{13}N_5$
Wash solids (no soap)	$C_{13}H_{28}O_{13}N_2$

These "canonical' formulas were developed to account for the major elements, C, H, N, and O found in human beings and plants. The elemental compositions were necessary to estimate oxygen requirements in a waste processor that would oxidize human and plant wastes. These food and waste chemical formulas have been used as indicated in Table 2.

In addition to the elements C,H,N, and O, other elements such as P, S, Ca, Mg, and K could be found in human wastes. These elements are all treated as ash consumed with food and rejected as ash wastes. The relative ash distribution was based on elemental compositions of freeze-dried urine and feces (Wydeven and Golub, 1990) .

Trace compounds, such as alcohols, ammonia, and methane generated by the human metabolic function, could significantly affect the sizing of trace contaminant control units and other processes interacting with them. These compounds would also impose consumable demands associated with processes for their removal. LiSSA uses estimates for the anticipated levels of release of these compounds into the human habitat without any explicit correlation with the composition of ingested food.

Hygiene water use and waste load estimates (Wydeven and Golub, 1990) on a 1 person-day basis are presented in Table 3.

PHYSICAL/CHEMICAL LIFE SUPPORT TECHNOLOGIES

Technologies are grouped as subsystem functional elements (SFEs) within subsystems. The SFE functions traded in this study include CO_2 removal, CO_2 reduction, and O_2 generation for the Air Revitalization (AR) subsystem; potable water (PW) processing, hygiene water (HW) processing, and urine processing for the Water Management (WM) subsystem; and drying and oxidation for the Solid Waste Treatment (SWT) subsystem. Data sources for technologies are given in Tables 4A, 4B, and 4C. A "validity level", as described in Table 5, is attributed to each technology based on JPL judgement. This validity level can be viewed as a relative uncertainty of the data for each technology. Correlations used to calculate the wet weight, dry weight, power, and volume of each technology is included in the LiSSA-TT spreadsheet. Descriptions and schematics of each technology included in this report can be found in the life support literature.

LIFE SUPPORT SYSTEM TECHNOLOGY TRADE RESULTS

In order to perform technology trades, a baseline system to trade against was chosen. Baseline technologies are not "baselined" identically in any known life support system design nor do they represent an optimal system configuration. They have been arbitrarily chosen as representatives of the technology functions constituting a physical-chemical life support system. Figure 5 shows the baseline system.

The technology trades were performed by substituting for a baseline technology one at a time. Twenty two cases were run with LiSSA-ST in ASPEN with the technology choices as identified in the Case Matrix (Table 6) . After running the 22 cases, results were imported into the LiSSA-TT spreadsheet program. System parameters chosen for the simulations are listed in Table 7. These parameters are defined for a Lunar Base with a crew size of 4 and ~~two~~ mission durations of 90 and 600 days.

The EBSS parameter provides for regenerable supplies other than air to meet the demand for consumables during emergencies caused by failure of, or unanticipated downtime for process hardware. EBSS is specified in days and must be selected to provide an adequate period for recovery from the emergency and restoration of regenerative operations. This parameter is also included in sizing storage tanks for additional supplies and accumulation of unprocessed wastes during the emergency periods.

EBSSA is a parameter similar to EBSS but for air alone and is specified in hours instead of days and primarily pertains to emergencies caused by failure of the carbon dioxide removal function. This parameter is ignored when the LiOH carbon dioxide removal option is enabled for such emergencies.

ESF, the exhaust storage factor, provides for reuse of supply storage tanks to store wastes and trash. Table 8 illustrates the role of ESF. A zero value for ESF is impractical since wastes have to be stored in the same supply storage tank containing fresh supply.

when the ESF parameter is set to 100, then twice the capacity for storage is provided at the start of the mission: one containing fresh supplies and the other empty at the start of the mission. At the end of the mission the supply storage tank is expected to be empty and the identical waste storage tank filled with wastes. When ESF is set to 50, then the supply storage capacity is split between two identical tanks at the start of the mission and a third tank of the same size provided to store wastes . When the third storage tank is filled up with wastes, one of the two supply storage tanks is expected to be empty to accommodate the rest of the wastes. At the end of the mission, there would be two storage tanks filled with wastes and one nearly empty storage tank available for any additional waste storage. Smaller values of ESF impose greater number of smaller storage tanks.

The results of the technology substitutions in terms of system wet weights for the 22 cases are presented for the Lunar Base mission durations of 90 days and 600 days in Figures 6A and 6B. The impact of technology substitutions on subsystem wet weights are shown in Figures 7-A and 7-B. Similar comparisons in terms of overall system power demand and subsystem power demand are shown in Figures 8-A and 8-B respectively.

Overall system weights vary between 3,900 kg and 4,500 kg for the 90 day mission and from 13,800 kg to 18,700 kg for the 600 day mission as seen in Figures 6-A and 6-B respectively. Note that, for both mission durations, the cases maintain their relative positions with a few exceptions. For example, in both the 9(I day mission and 600 day missions, Case 10 pertaining to the use of Water Vapor Electrolysis technology for O_2 generation, shows the minimum weight; however, Case 22 (supercritical water oxidation for solids waste treatment) has the maximum weight for the 90 day mission but Case 6 (non-regenerative LiOH for CO_2 removal) , pertaining to nonregeneration of oxygen, is the heaviest for the 600 day mission. In general, nonregenerative system/subsystem configurations would impose increasing weight penalties with increasing mission duration. On the other hand, Case 7 which provides for the regeneration of oxygen using Sabatier technology to recover O_2 in the form of condensate from CO_2, turns out to be the second heaviest system as the mission duration is increased to 600 days. This is due to the need to trash hydrogen in the form of methane and the consequent need to store water to provide for the additional H_2 makeup required(via H20 electrolysis) . As mission duration is increased, the weight of consumable supplies to be stored at the start of the mission increasingly dominates over process equipment weight and eventually, for extremely long durations, the demand for consumable supplies dominates the total system weight.

The dominance of nonregenerable supplies is readily seen by a comparison of various subsystem weights constituting the total system weight as shown in Figures 7-A and 7-B. In these figures, storage subsystem weights include the weights of consummables and their containers. By keeping the crew size the same for both the 90 and 600 day missions, the differences between the two figures are entirely due to differences in the demand for consumable supplies. The weight of process equipment, being a function of crew size only, is the same for the two figures.

Since process equipment is identical with respect to mission duration, the power demand summaries shown in Figures 8-A and 8-B are identical for either 90 day or 600 day missions. The system power use ranges from a low of 3,700 watts for Case 6 to a high of 7,000 watts for Case 18. Cases 18 through 22 are significantly higher than other cases primarily due to the additional power required for solid waste treatment technologies. From Figure 8-B, it is clear that for all cases, the air revitalization (AR) subsystem is the largest consumer of power. The water management (WM) subsystem is roughly 1/4 to 1/2 that of the AR subsystem; the solids waste treatment (SWT) subsystem is less than the WM subsystem with the exception of Case 18.

SYSTEM CONFIGURATIONS TO MINIMIZE POWER

The LiSSA tool can be used to search for optimum process combinations to minimize power using regenerative life support technologies. For this analysis, 6 configurations were constructed with the technology choices as listed in Table 9.

Case 4 was chosen from the original 22 cases as a baseline to compare different configurations. Case 4, which is called MPBL, is compared with the other configurations in Figures 9-A for overall system power and Figure 9-B for overall system weight. Case 4 regenerates all of its oxygen but not all of its water requirements .

Case MP1 is a combination of some of the technologies that have low power requirements from the technology trades performed above. Case 4 does not regenerate all of its water requirements; for the MP1 configuration, excess water is produced. It should be noted that when using the CO2EL/BD process, most of the metabolic oxygen required is regenerated directly without oxygen generation through electrolysis of water. To meet the deficit in required oxygen, the WVE process is utilized.

Case MPIA is identical to MP1 with regard to technology choices. However, the potable water processing unit is configured to accept only enough feed to produce the required potable water product. If processing 100% of the feed results in an over-production of potable water, then a portion of the feed is bypassed and routed to a waste stream bus.

Case MPIB is also identical to MP1 and MPIA with regards to technology choices. However, if there is an excess of hygiene water produced over the requirement, then the urine processing unit is configured to accept only enough feed such that the excess is eliminated. Hence, this case sets UP a system to produce only the exact requirements of both potable and hygiene water.

Case MP2B is identical to MP1B with the exception of the use of Sabatier for CO_2 reduction. In this simulation, the amount of CO_2 fed to the unit is based on the available H_2 produced from the 0_2 generation process. This results in some of the CO_2 bypassing the CO_2 reduction process and thereby being routed to either venting or trash storage.

Case MP3B is a case where O_2 is not regenerated while maintaining H_2O regeneration. Hence, the only requirement for air revitalization is to remove the CO_2 which is done by the regenerative APC CO_2 removal process.

Figure 9-A shows how the overall system power is reduced relative to Case 4 which requires 4,617 watts. An 800 watt saving from MPBL to MP1 is realized by combining the best performers with respect to power. By minimizing the amount of potable water processing to only that required, 30 additional watts are saved based on the comparison of Cases MP1 and MP1A; 20 more watts are saved by minimizing the amount of urine being processed by TIMES. By switching to Sabatier, where only the CO_2 is reduced with the available H_2, 260 watts can be saved as seen from comparing Case MP2B to MP1B. Case MP3B, which does not regenerate O_2, shows an additional 830 watt advantage over Case MP2B.

Figure 9-B shows the effect on overall system weight as the power is reduced; Case 4 has a wet weight of 14,161 kg, In comparing Case 4 with MP1, it is seen that regenerating all of the water comes at the expense of additional chemical supplies. By reducing the amount of processing, there are slight reductions in chemical and system weights as shown by Cases MPIA and MP1B. By choosing the Sabatier process where only part of the CO_2 is reduced, the system weight is reduced by 750 kg; most of this weight reduction is due to the decreased weight of chemical supplies as non-regenerable cartridges. These cartridges are required for carbon deposition in the CO2EL/BD process that is not required for the Sabatier process. The MP3B case, which does not regenerate 0_2, has a weight penalty of over 7,700 kg relative to Case 4 but a 1,960 watts advantage.

SYSTEM CONFIGURATION TO MINIMIZE WEIGHT

Similar to the minimizing power search, the process configuration to minimize overall system weight can also be sought. For this analysis, 5 configurations were constructed with the technology choices as listed in Table 10.

Case 10 was chosen from the original 22 cases as a baseline to compare different configurations. Case 10, which is called MWBL, is compared with the other configurations in Figures 1O-A for overall system weight and Figure 1O-B for overall system power. Case 10 regenerates all of its oxygen but not all of its water requirements . The overall system weight is 13,779 kg and system power, 5,083 watts.

Case MWIA combines some of the technologies that individually traded well in the above technology trades with regard to overall system weight. In addition, excess waste water feed (relative to potable water requirements) was routed to hygiene processing. Also, excess urine feed (relative to hygiene water requirements) was discarded. This configuration completely regenerates oxygen but does not completely regenerate all the water requirements as water is lost in the RO brine.

case MW1B is identical to MW1A with the exception that RO brine from hygiene processing is routed to urine processing. Also, *excess* urine feed (relative to hygiene water requirements) was discarded. This configuration completely regenerates all oxygen and water requirements with some excess water available.

Case MW1D is identical to MW1B in configuration; the difference is in water contained in the stored food. The previous cases have used food as indicated above which is derived from the food proposed for Space Station. Case MWID (and MW2D) have reduced the amount of water in the food from a water/dry food ratio of 1.83 to 0.65. This ratio is similar to that currently being used for the Space Shuttle. This configuration completely regenerates all oxygen and water requirements.

Case MW2D is similar to Cases MW1B and MW1D with the exception of using Sabatier in place of CO2EL/BD for CO_2 reduction; the water/dry food ratio is set at 0.65. This configuration completely regenerates all oxygen and water requirements with some excess water available.

Figure 1O-A shows the relative weight advantages for the different configurations. Three significant advantages can be seen due to the following: 1) Judicious routing/rerouting excess feeds and brines in the WM subsystem: this results in a reduction of about 690 kg; 2) Changing the water in the stored food: this results in a reduction of about 2,100 kg; and 3) Substituting Sabatier for C02EL/BD for CO_2 reduction: this results in a reduction of about 600 kg. It should be noted that these steps result in weight savings when the system can regenerate all the oxygen and water requirements. If a system configuration does not regenerate all the oxygen and water, this might not apply.

Figure 1O-B shows the power advantages even though the configurations were set to minimize the overall system wet weight . As shown, Cases MW1A, MW1B, and MWID show a 900 watt advantage from Case 10. Using Sabatier (MW2D) reduces the power demand by an additional 250 watts.

is LSS to be read as "LSS" or as what the abbreviation represents?)

CONCLUSIONS ? (

The GMFS architecture described in this paper can encompass all functional elements of a P/C CLLS system. The GMFS concept enables an LSS analyst to synthesize, model, analyze, and quantitatively compare complex closed-loop and partially closed-loop configurations. The methodology established in the LiSSA tool can be extremely useful to compare technologies and system configurations for minimizing LSS power and weight for various manned missions.

ACKNOWLEDGEMENTS

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NOTATION

2 BMS	Two bed molecular sieve
4 BMS	Four bed molecular sieve
ACRS	Advanced carbon reactor system
AIRE	Air evaporator
APC	Air polarized concentrator
AR	Air revitalization
ASCII	American standard code for information interchange
ASPEN Plus	A state-of-the-art chemical process simulation software program from AspenTech Inc.
BL	Baseline
CLLS	Closed loop life support
COMB	Combustion
CO2EL/BD	CO_2 electrolysis/Boudouard reactor
CPGM	Concentrated polluted gas mix
EBSS	Emergency backup supply storage
EBSSA	Emergency backup supply storage for air
EDC	Electrochemical depolarized concentrator
ELDI	Electrochemical deionization
ESF	Exhaust storage factor
FD	Freeze drying
GMFS	Generic modular flow schematic
GTVO	Gaseous trash venting option
HW	Hygiene water; used for external body, dish, clothes, etc. washing
ICES	International Conference on Environmental Systems
JSC	Johnson Space Center
JPL	Jet Propulsion Laboratory
LiOH	Lithium hydroxide
LiSSA	Life support systems analysis
LiSSA-ST	Life support systems analysis-simulation tool
LiSSA-TT	Life support systems analysis-trade tool
LTVO	Liquid trash venting option
MDSSC	McDonnell Douglas Space Systems Company
MF	Multifiltration
MP	Minimum power
MPBL	Minimum power baseline
MSFC	Marshall Space Flight Center
MW	Minimum weight
MWBL	Minimum weight baseline
OD	One-way duration
P/C	Physical chemical
PC	Personal computer
PC/LSS	Physical/chemical life support system
PW	Potable water: ingested by humane
RLS	Regenerative life support
RO	Reverse osmosis
RTOP	Research and technology objectives and plans
SAE	Society of Automotive Engineers
SAWD	Solid amine water resorption
S/C	Spacecraft
SCWO	Supercritical water oxidation
SFE	Subsystem functional element
SFWE	static feed water electrolysis
SPELF	Solid polymer electrolyte
SS	Subsystem
SSF	Space Station Freedom
STDO	Solids trash dumping option
SWT	Solid Waste Treatment
TD	Thermal drying
TCS	Total crew size
TCC	Trace contaminant control
T & HC	Temperature and humidity control
TIMES	Thermoelectric integrated membrane evaporation system
VCD	Vapor compression distillation
VPCAR	Vapor phase catalytic ammonia removal
WM	Water management
WOX	Wet oxidation
WP	Water processing
WR	Water recovery
WVE	Water vapor electrolysis

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Table 1A Storage Operations Subsystem SFES

SFE#	Description
0A	Fresh air
0B	Oxygen
0C	Nitrogen
0D	Potable water
0E	Hygiene water
0F	Food
0G	Other ingestible: medicines, pills, etc.
0H	Use/trash supplies: papers, bags, and other supplies that the crew physically can separate and dispose into trash disposal or trash storage containers
0I	Chemical supplies: chemicals or chemical processing materials that are used in LSS processing of wastes
0J	Other supplies: materials used that are eventually treated in LSS processing units
0K	Circulating air
0L	Non-polluted gaseous mixture
0M	Concentrated polluted gas mixture
0N	Gaseous trash
0O	Hydrogen
0P	Methane
0Q	Carbon dioxide
0R	Wash water
0S	Urine flush
0T	Concentrated aqueous polluted mixture
0U	Liquid trash
0V	Concentrated non-aqueous liquid polluted mixture
0W	Condensate
0X	Solid waste
0Y	Solid trash

Table 1B Human Habitat Subsystem SFES

SFE#	Description
11	Metabolic Operations
12	Kit then
13	Dishwash
14	Toilet
15	Wash and Shower
16	Laundry
17	Manicure and Personal Hygiene
18	Habitat Cleaning
19	Habitat Lighting

Table 1C Temperature and Humidity Control Subsystem SFEs

SFE#	Description
21	Air Heating
22	Air Cooling and Humidity Condensation
23	Dehumidification (sorbent/dessicant)
24	Humidification
25	Water Heating
26	Water Cooling
27	Air Circulation and Ventilation

Table 1D Air Revitalization Subsystem SFES

SFE#	Description
31	Dust Separation
32	Vapor and Pollutant Separation
33	CO_2 Removal
34	CO_2 Reduction
35	Trace Pollutant Sorption/Oxidation
36	Trace Pollutant Scrubbing
37	Oxygen Generation
38	O_2-N_2 Makeup

Table 1E Water Management Subsystem SFES

SFE#	Description
41	Water Generation (fuel cell, etc.)
42	Non-Aqueous Phase Separation
43	Suspended Solids Filtration
44	Potable Water processing
45	Trace Organics Oxidation
46	Hygiene Water processing
47	Urine Processing

Table 1F Solids Treatment Subsystem SFES

SFE#	Description
51	Fuel (production or processing)
52	Grinding
53	Drying
54	Pyrolysis
55	Oxidation

Table 1G Master Computer Control and Major Monitoring Instrumentation (MCC & MMI) SFES

P	Descrip ion
	Master Control Computer
62	Gaseous Trace Contaminant Monitor
63	Water Trace Contaminant Monitor
64	Biological/Micro-organisms (uO) Contaminant Monitor

Table 1H Trash Disposal Subsystem SFES

SFE#	Description
71	Gas Compression and Stabilization
72	Liquid Sterilization and Stabilization
73	Solids Compaction and Stabilization

Table 2 Metabolic Mass Balance (kg/person-day)

INPUTS	CARBON	HYDROGEN	OXYGEN	NITROGEN	ASH	TOTALS
1. DRY FOOD						
Protein, C_4H_5ON	0.07-70	0.0081	0.0257	0.0225		0.1332
Carbohydrate, $C_6H_{12}O_6$	0.1489	0.0250	0.1984			0.3723
Fat, $C_{16}H_{32}O_2$	0.0858	0.0144	0.0143			0,1145
Minerals, Ash					0.0095	0.0095
2. LIQUIDS (WATER)						
Drink		0.1802	1.4298			1.6100
Food Preparation		0,0884	0.7016			0.7900
Food Water Content		0.1287	1.0213			1.1500
3. GASES						
Oxygen			0.8359			0.8359
INPUT SUMS	0.3118	0.4448	4.2270	0.0225	0.0095	5.0155
OUTPUTS						
1. SOLID WASTES						
Urine, $C_2H_6O_2N_2$	0.0160	0.0040	0.0213	0.0187	0.0077	0.0678
Feces, $C_{42}H_{69}O_{13}N_5$	0.0177	0.0024	0.0073	0.0024	0.0018	0.0318
Sweat, $C_{13}H_{28}O_{13}N_2$	0.0074	0.0014	0.0099	0.0013		0.0200
2. LIQUIDS (WATER)						
Urine		0.1693	1.3440			1.5133
Feces		0.0102	0.0806			0.908
Sweat & Perspiration		0.2574	2.0429			2.3003
3. GASES						
Carbon dioxide	0.2706		0.7209			0.9915
OUTPUT SUMS	0.3118	0.4448	4.2270	0.0225	0.0095	5.0155

Table 3 Hygiene Water Use (kg/per person day)

Water Use:	
Oral hygiene H_2O	0.36
Hand/face Wash H_2O	1.81
Shower H_2O	5.44
Clothes wash H_2O	12.47
Dish wash H_2O	5.44
Flush H_2O	0.49

	26.01
Waste Loads:	
Hygiene H_2O	7.17
Latent hygiene H_2O	0.44
Clothes wash H_2O	11.87
Latent clothes wash H_2O	0.60
Dish wash H_2O	5.41
Latent dish wash H_2O	0.03
Flush H_2O	0.49
	---- --
	26.01

Table 4-A Air Revitalization Subsystem Technology Data Sources

SFE	TECHNOLOGY	REFERENCE	VALIDITY LEVEL
CO_2 Removal	4 BMS	MDSSC, 1989, NASA-MSFC, 1987	3
	2 BMS	MDSSC, 1989	4
"	EDC	MDSSC, 1989 NASA-MSFC, 1987 Lin, 1992	4
" "	APC	MDSSC, 1989 NASA-MSFC, 1987 Lin, 1992	?
"	SAWD	MDSSC, 1989 NASA-MSFC, 1987	-1
" "	LiOH	Hamilton Standard, 1980	3
C02 Reduction	Bosch	MDSSC, 1989 NASA-MSFC, 1987	3
" "	Sabatier	MDSSC, 1989 NASA-MSFC, 1987	3
" "	ACRS	MDSSC, 1989 NASA-MSFC, 1987	4
" "	CO2EL/BD	MDSSC, 1989 NASA-MSFC, 1987	7
02 Generation	SFWES	MDSSC, 1989 NASA-MSFC, 1987	3
" "	WVE	MDSSC, 1989 NASA-MSFC, 1987	7
" "	SPELF	MDSSC, 1989 NASA-MSFC, 1987	7

Table 4-B Water Management Subsystem Technology Data Sources

SFE	TECHNOLOGY	REFERENCE	VALIDITY LEVEL
Potable H20 Processing	MF	MDSSC, 1989, NASA-MSFC, 1987	3
•	RO	MDSSC, 1989 NASA-MSFC, 1987	3
'	ELDI	MDSSC, 1989 NASA-MSFC, 1987	7
Hygiene H?O Processing	RO	MDSSC, 1989 NASA-MSFC, 1987,	3
• •	MF	MDSSC, 1989 NASA-MSFC, 1987	3
Urine Processing	TIMES	MDSSC, 1989 NASA-MSFC, 1987	3
· ·	VC D	MDSSC, 1989 NASA-MSFC, 1987	3
• •	VPCAR	MDSSC, 1989 NASA-MSFC, 1987	7
• •	AIRE	MDSSC, 1989 NASA-MSFC, 1987	7

Table 4-C Solid Waste Treatment Subsystem Technology Data Sources

SFE	TECHNOLOGY	REFERENCE	VALIDITY LEVEL
Drying	FD	Labconco, 1987	7
'	TD	Fisher, 1988	7
Oxidation	COMB	Labsk et al., 1972 Slavin et al., 1986	7
'	Wox	Slavin et al., 1986 Jagow et al., 1970	7
'	SCWO	MDSSC, 1989 Slavin et al., 1986 Hong et al., 1987 Freeman, 1989	7

Table 5 Validity Level Definitions

VALIDITY LEVEL	DESCRIPTION
1	Measurement
2	Calculated from a dimensioned drawing with known materials of construction
3	Estimated from scaling procedure using data from 1 and/or 2 above
4	Estimated from high validity data for similar equipment
5	Estimated from detailed paper design for nonexistent hardware
6	Invalidated third party estimates
7	"Engineering judgement"

Table 6 Case Matrix of Technology choices

CASE NO.	AR SUBSYSTEM CO2 REMOVAL	CO2 REDUCT 10N	O2 GENERATION	WM SUBSYSTEM POTABLE H2O PROCESSING	HYGIENE H2O PROCESSING	URINE PROCESSING	SWT SUBSYSTEM DRY I NC	OXIDATION
1	4BMS	BOSCH	SFWE	MF	RO	TIMES	NONE	NONE
2	2BMS		.	.	.	.	.	.
3	EDC	.	.		'	.	.	.
4	APC	.	.	.		.	.	.
5	SAWD	.	.	.	.	.	.	
6	LIOH	NONS	.	.	.	.	.	
7	4BMS	SABATIER	.	.	.	.	.	
8	"	ACRS	.	.	.	.	.	.
9	"	CO2EL/BD	"	.	.	.	.	.
10	"	BOSCH	WV's	.	.	.	.	.
11	"	.	SPELF	.	.	.	.	.
12	"	.	S FWE	RO	.	.	.	.
13	.	.	.	ELDI	.	.	.	.
14	"	.	.	MF	MF	.	.	.
15	•	.	.	.	RO	VCD	.	.
16	"	.	.	.	.	VPCAR	.	.
17	"	.	.	.	.	AIRE	.	.
18	.	.	.	.	.	TIMES	FD	.
19	"	.	.	.	.	.	TO	.
20	"	.	.	•	.	.	NONE	COMB
21	"	.	'	.	.	.	•	WOX
22	"	.	.	•	.	.	.	SCWO

Table 7 LiSSA-TT Parameter Choices

Parameter	LiSSA-TT Variable Name	Value
Total crew size	TCS	4
Mission duration	OD	90 and 600
Emergency backup supply storage (days)	EBSS	5
Emergency backup supply storage for air (hrs)	EBSSA	0
Exhaust storage factor(%)	ESF	10
Gaseous trash venting option (vent=1 or store=0)	GTVO	1
Liquid trash venting option (vent=1 or store=0)	LTVO	1
Solids trash dumping option (dump-1 or store=0)	STDO	1

Table 8 Exhaust Storage Factor and Storage Tanks

ESF %	# OF IDENTICAL WASTE STORAGE TANKS AT START OF MISSION	TOTAL STORAGE VOLUME AS A PERCENTAGE OF SUPPLY STORAGE VOLUME
0	1	100
100	1	200
50	2	150
25	4	125
10	10	110
5	20	105

Table 9 Technology Choices to Minimize System Power

CASE	AR SUBSYSTEM			WM SUBSYSTEM			SWT SUBSYSTEM
	C02 REMOVAL	c02 REDUCTION	O2 GENERATION	POTABLE H2O PROCESSING	HYGIENE H2O PROCESSING	URINE PROCESSING	DRYING or OXIDATION
MFBL : Case 4	APC	BOSCH	SFWE	MF	RO	TIMES	NONE
MP1	·	CO2EL/BD	WVE	MF	MF	•	•
MPIA	•	·	•	MF (minimize feed via bypassing)	•	•	•
MP1B	•	•	•	•	•	• (minimize feed via bypassing)	•
MP2B	•	sAB (minimize feed via bypassing)	•	•	•	•	'
MPWR3B		NONE	NONE	·	·	•	·

Table 10 Technology Choices to Minimize System Weight

CASE	AR SUBSYSTEM			WM SUBSYSTEM			SWT SUBSYSTEM
	CO2 REMOVAL	CO2 REDUCTION	O2 GENERATION	POTABLE H 20	HYGIENE H20 PROCESSING	URINE PROCESSING	DRYING or OXIDATION
MWBL (Case 10)	4 BUS	Bosch	WVE	MF	RO	TIMES (minimize feed via bypassing)	HONE
MW1A	2BMS	CO2EL/BD	•	MF (minimize feed via by-passing to hygiene proc.)		•	
MW1B	·	·	·		•	•	•
MW1D	•	•	•		• (route RO brine to urine processing)	• (process RO brine)	•
MW2D	•	SAB (minimize feed via bypassing)	•	•	•	•	•

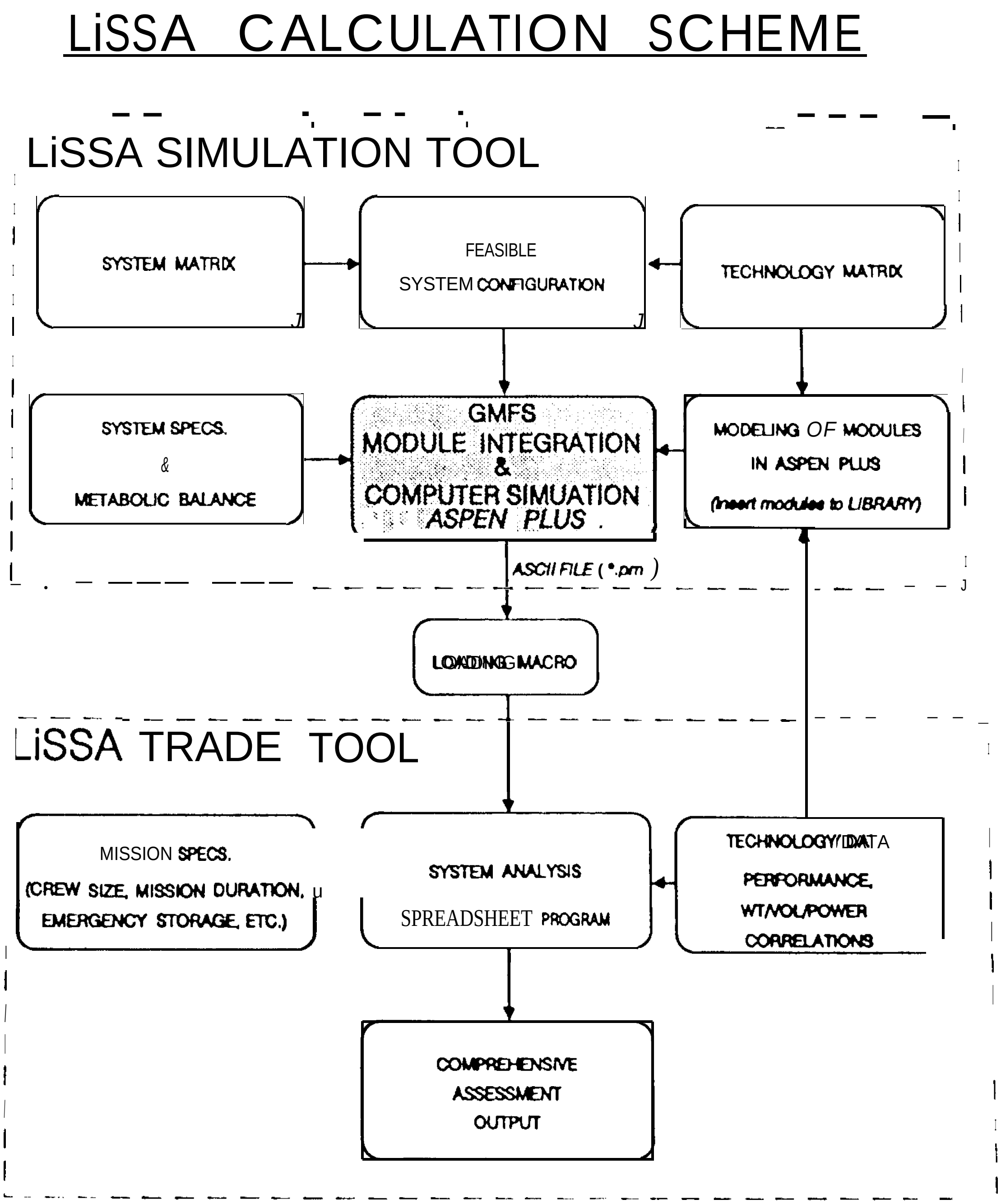


Figure 1 LiSSA Methodology

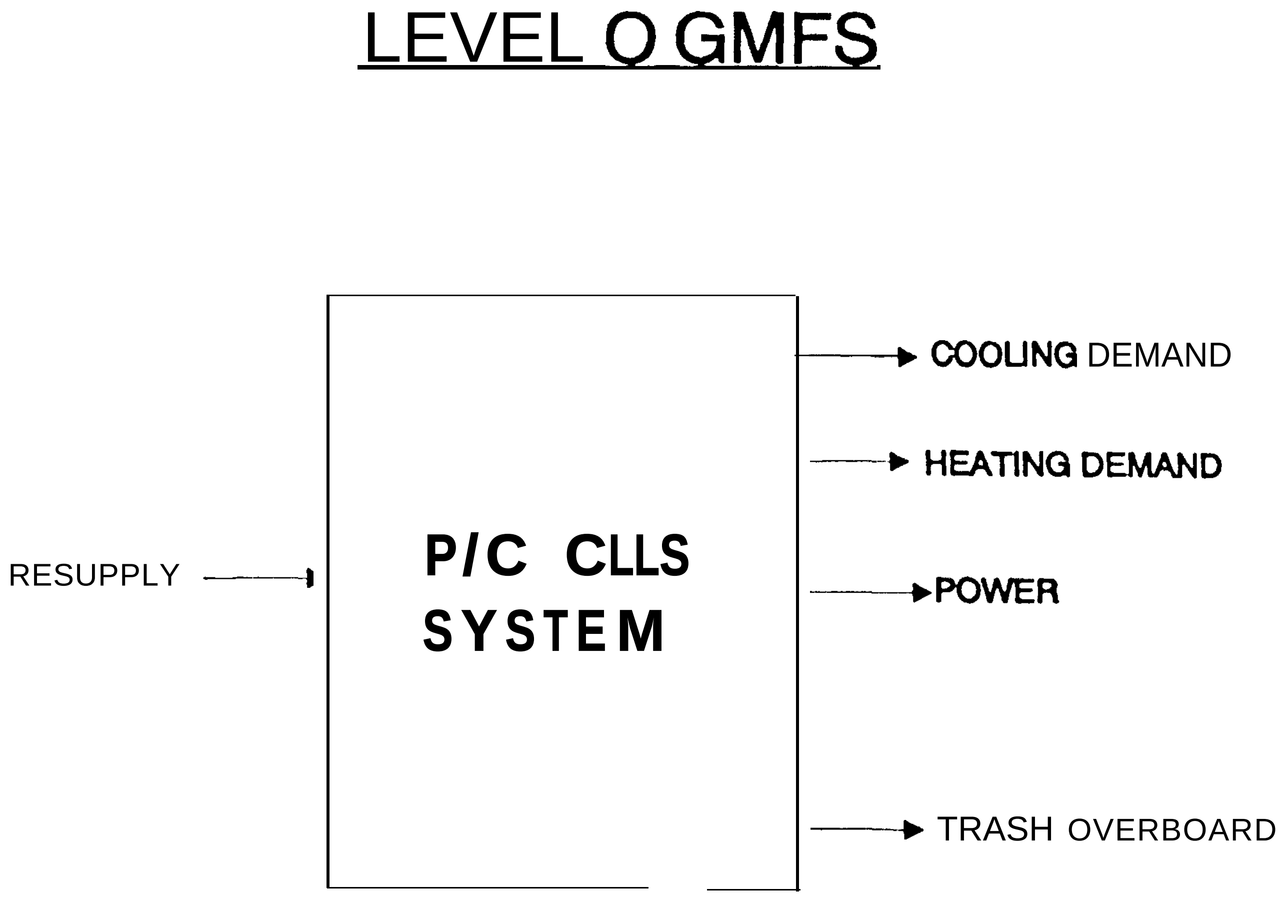


Figure 2-A Level 0 Generic Modular Flow Schematic

LEVEL I GMFS

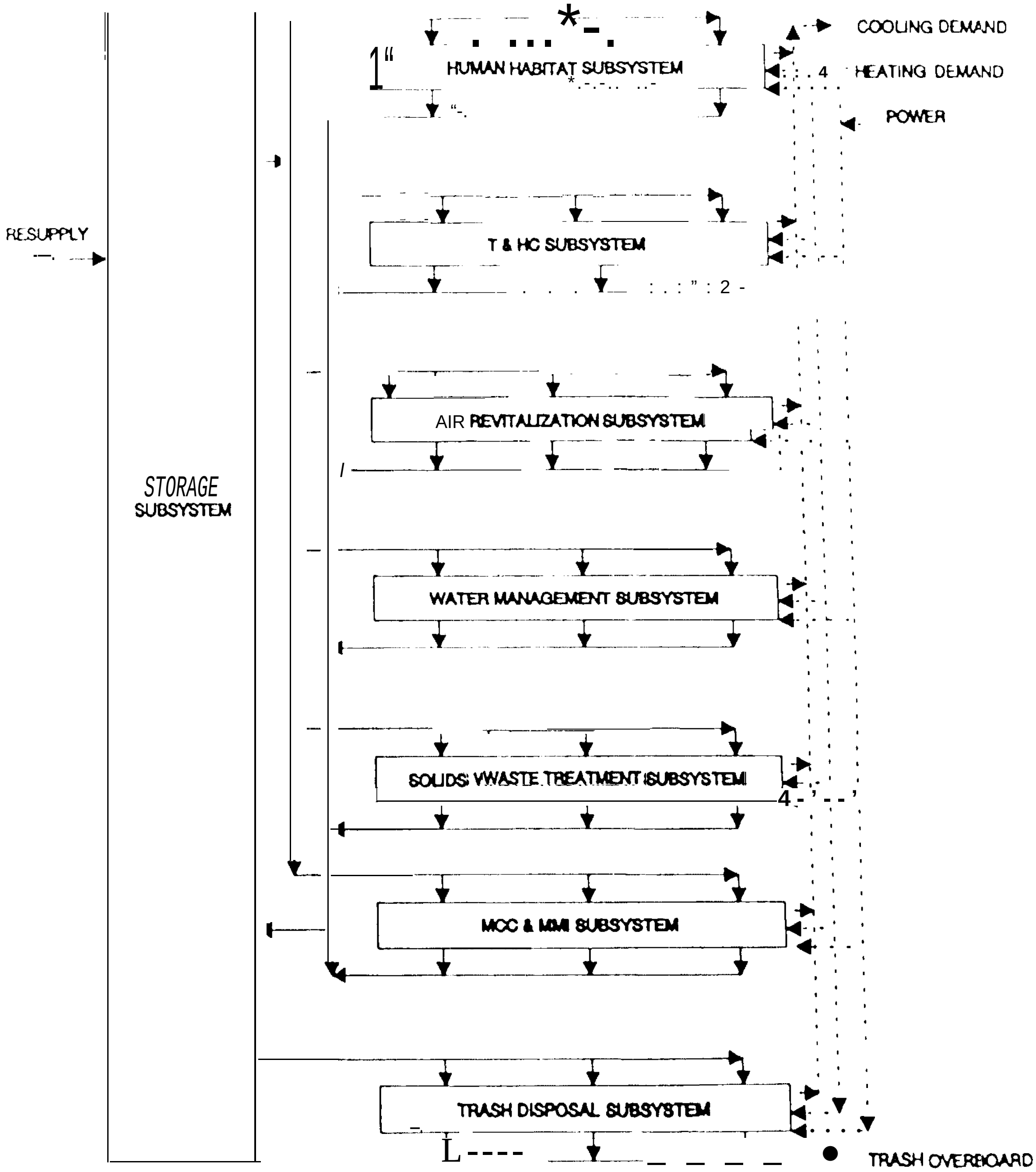


Figure 2-B Level I Generic Modular Flow Schematic

GMFS LEVEL II

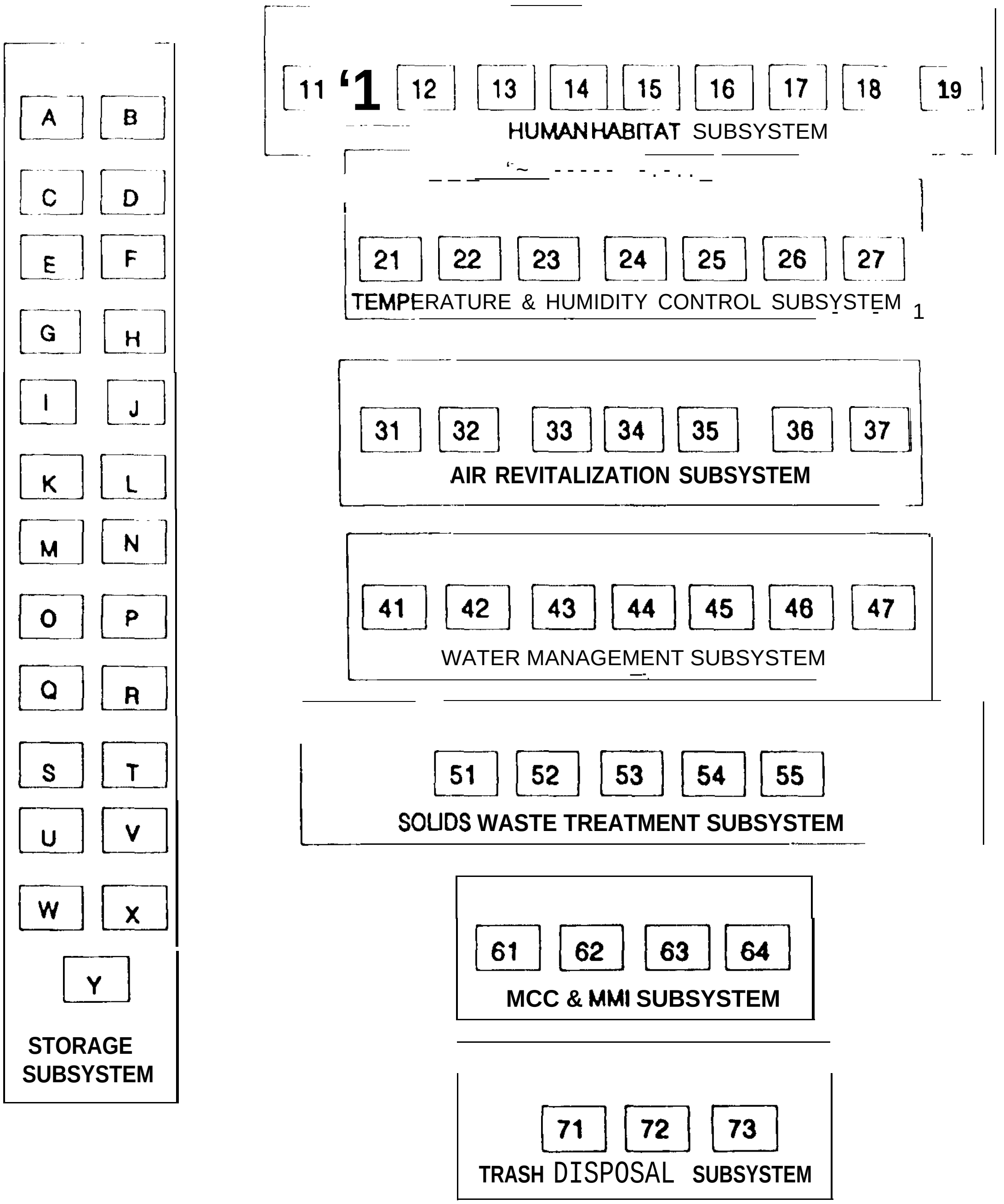


Figure 2-C Level II Generic Modular Flow Schematic

GMFS LEVEL III = SFE # 46

DISSOLVED ORGANICS/uO and/or INORGANIC SEPARATION: RO/MF TECHNOLOGY

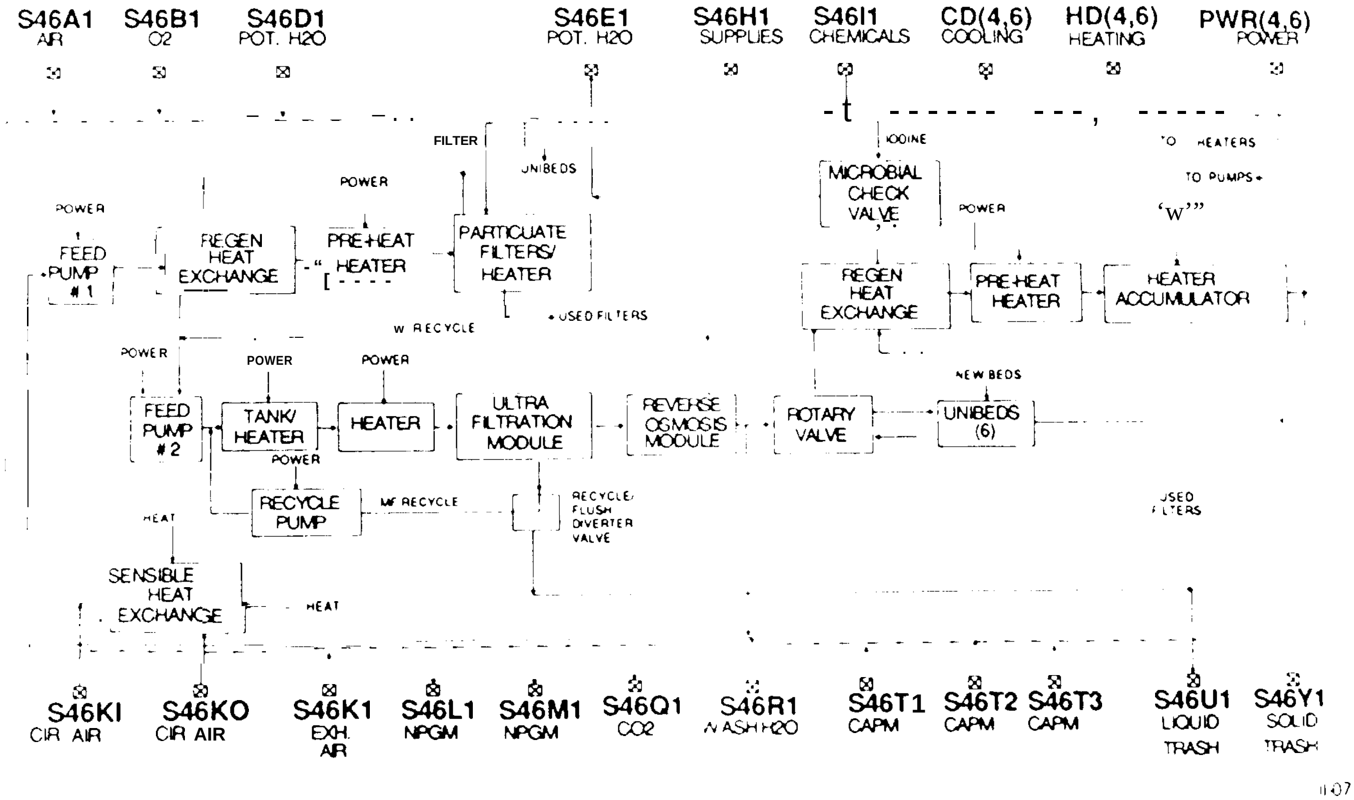


Figure 2-D Level III Generic Modular Flow Schematic

<u>GMFS LEVEL II:</u>
<u>HYGIENE WATER DISTRIBUTION</u>
<u>WATER MANAGEMENT SUBSYSTEM</u>

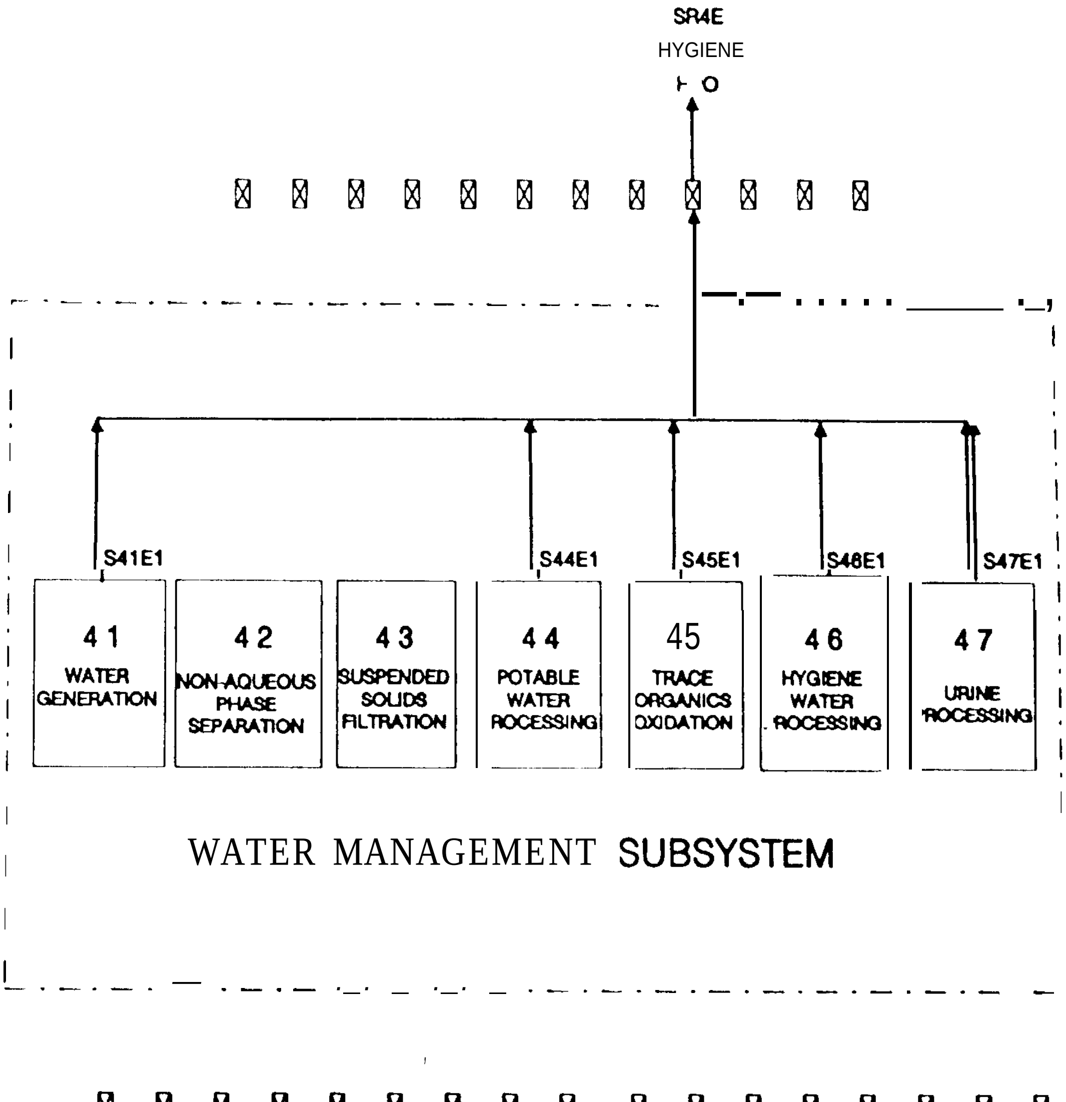


Figure 3-A GMFS Level II: Water Management Subsystem - Hygiene Water Distribution

GMFS LEVEL I: HYGIENE WATER DISTRIBUTION

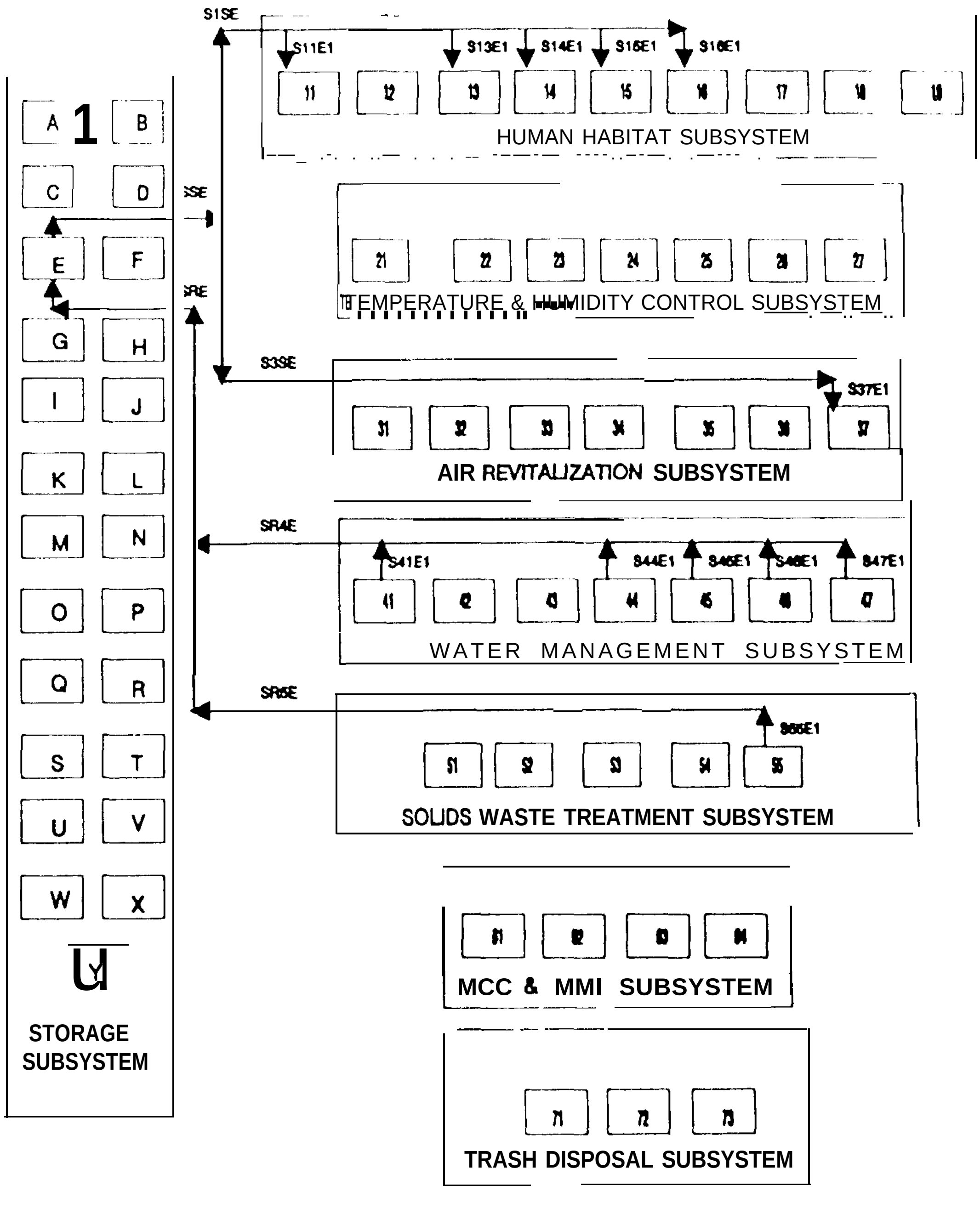


Figure 3-B GMFS Level I: System Hygiene Water Distribution

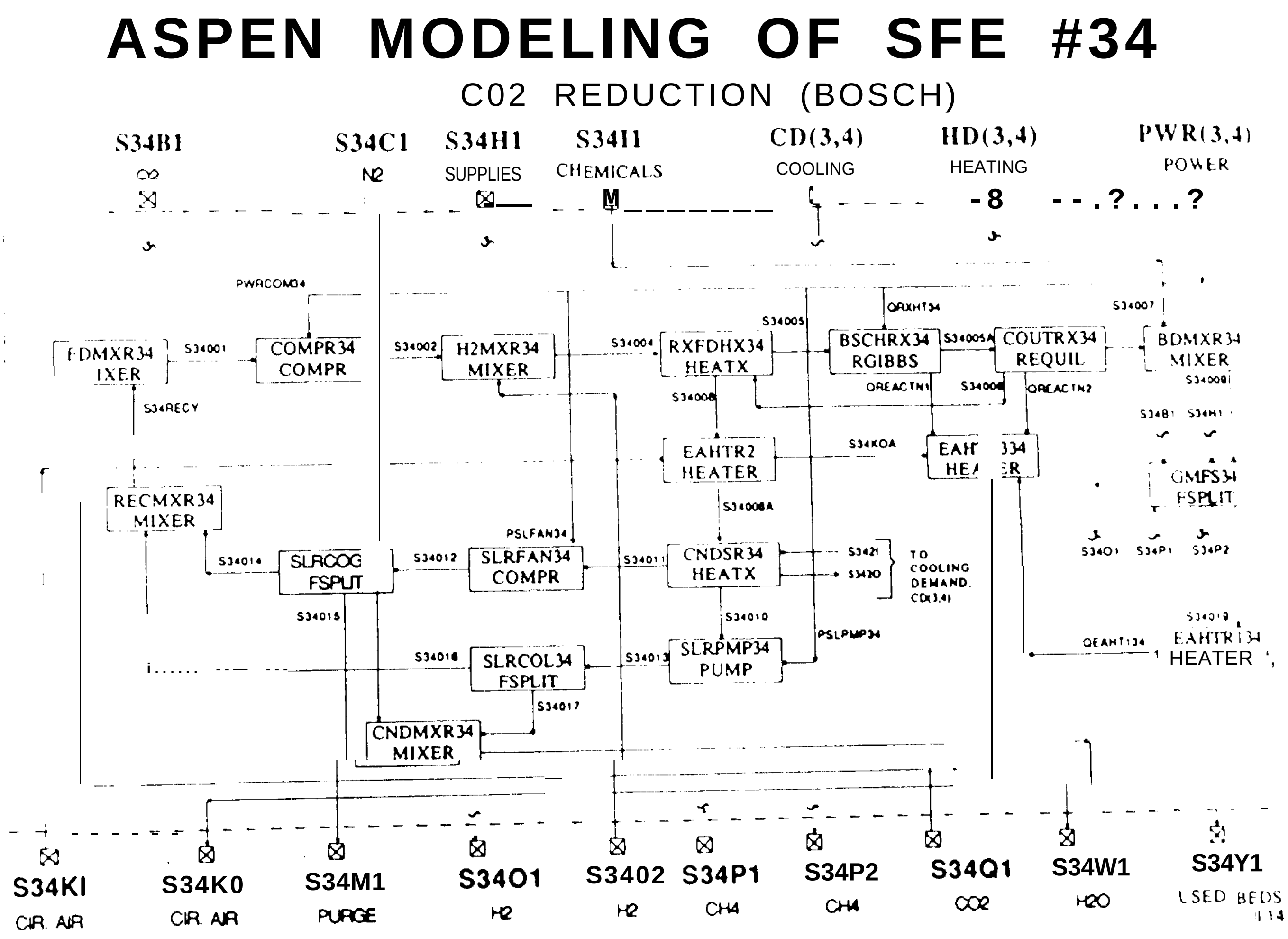


Figure 4 Level III ASPEN Modeling of SFE #34 - CO_2 Reduction (Bosch)

BASEUNE LIFE SUPPORT SYSTEM CONFIGURATION (CASE 1)

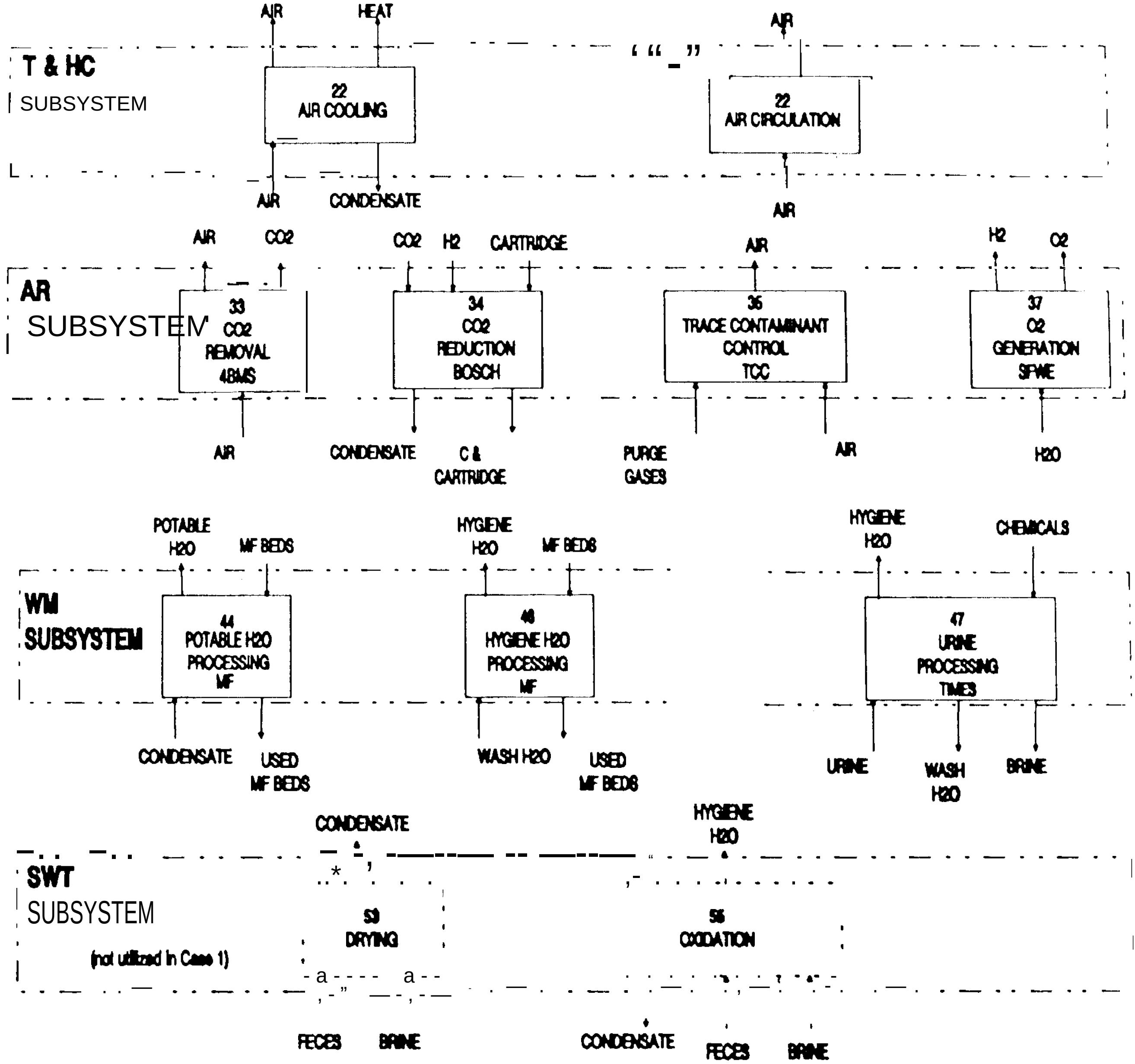


Figure 5 Baseline Life Support System Configuration

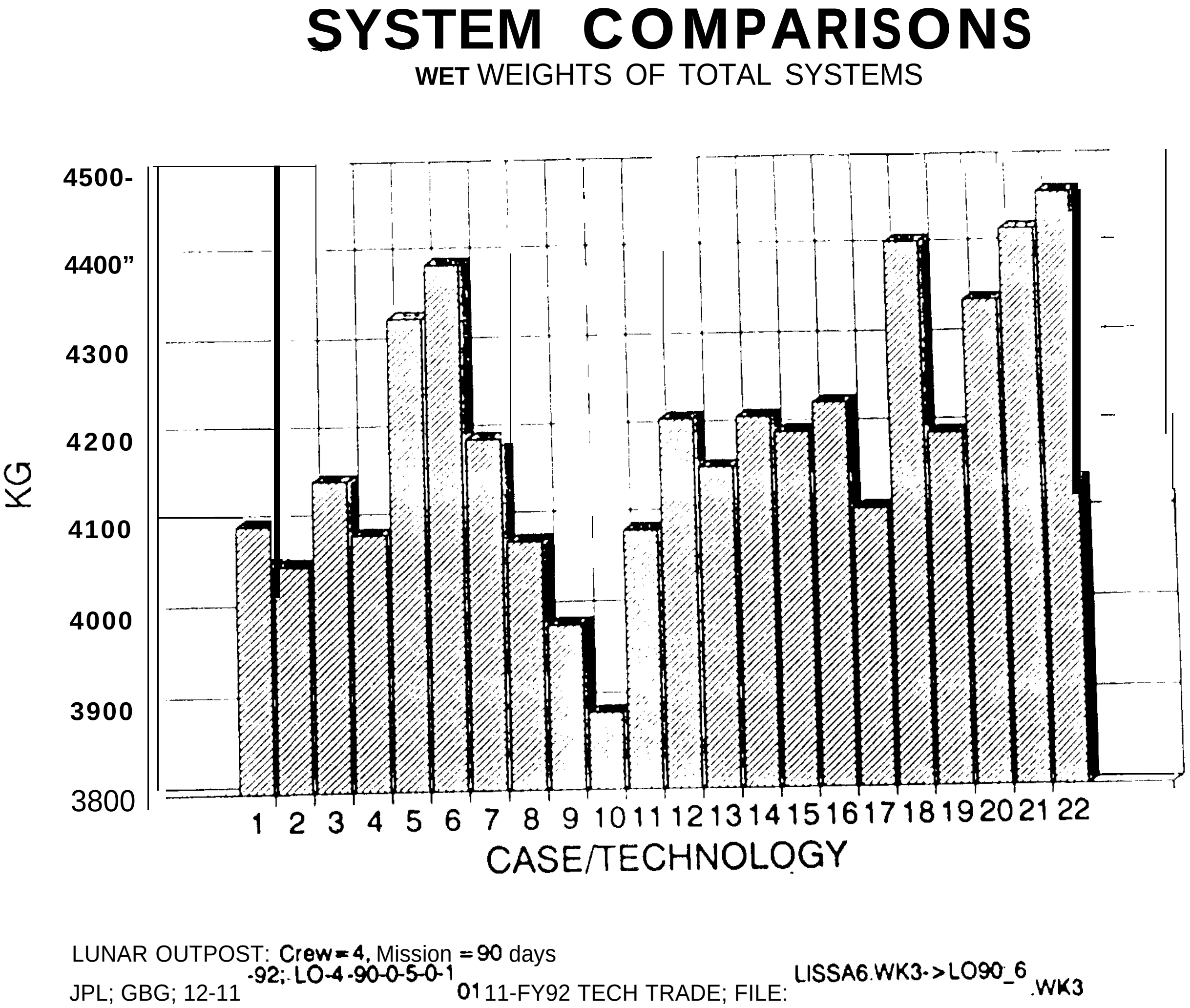


Figure 6-A Total System Weight Comparisons (90 day mission)

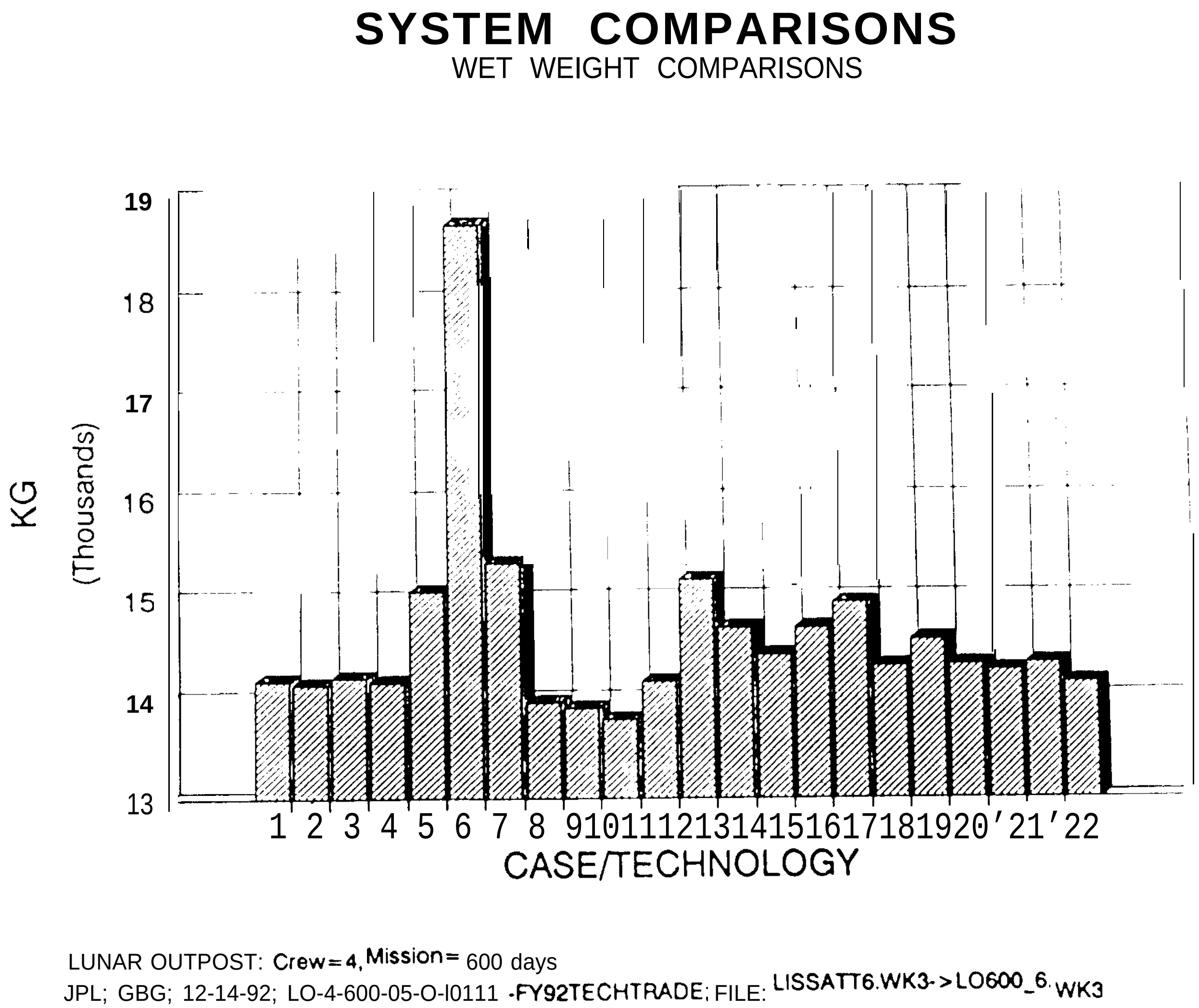


Figure 6-B Total System Weight Comparisons (600 day mission)

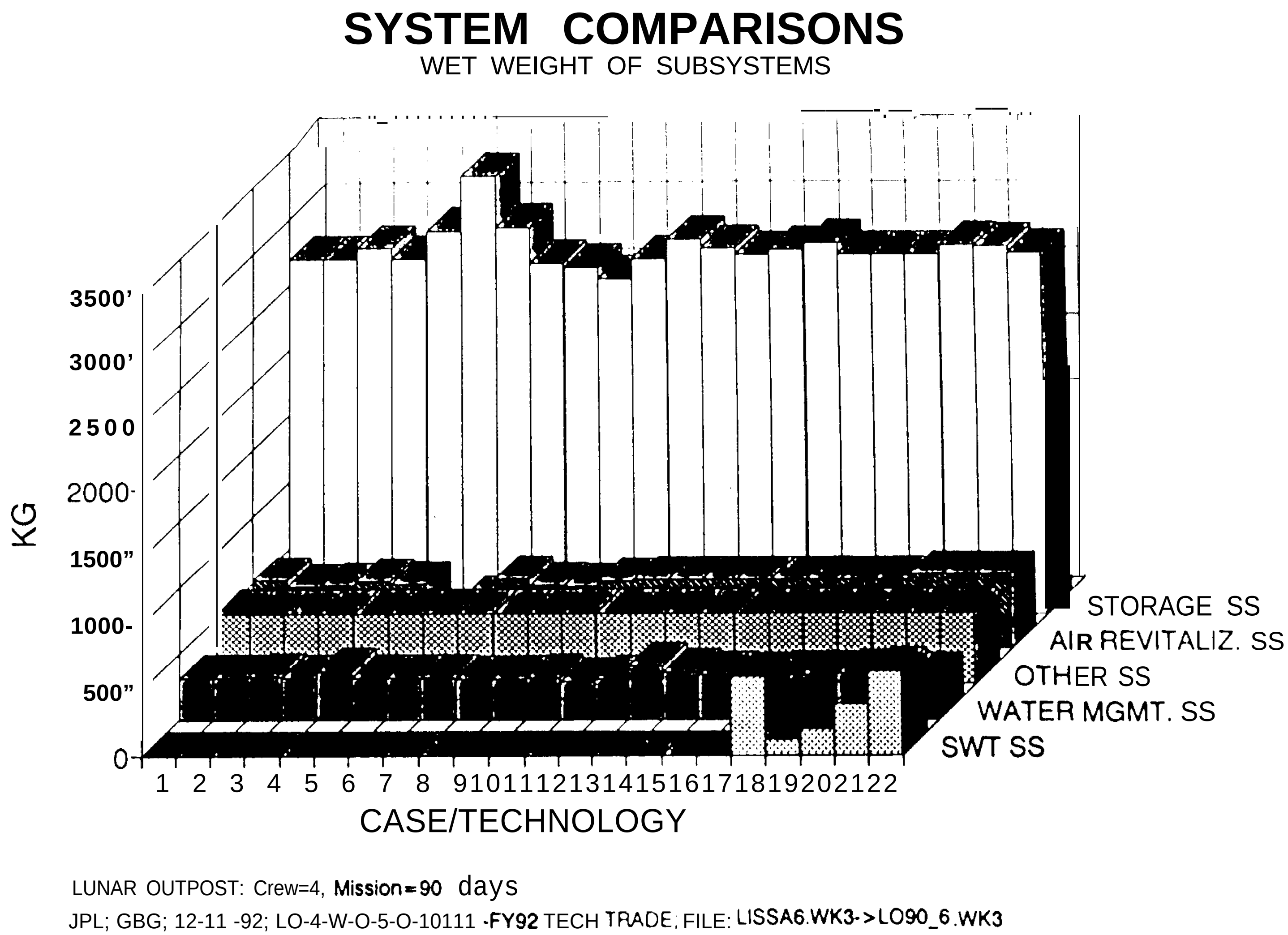


Figure 7-A Subsystem Weight Comparisons (90 day mission)

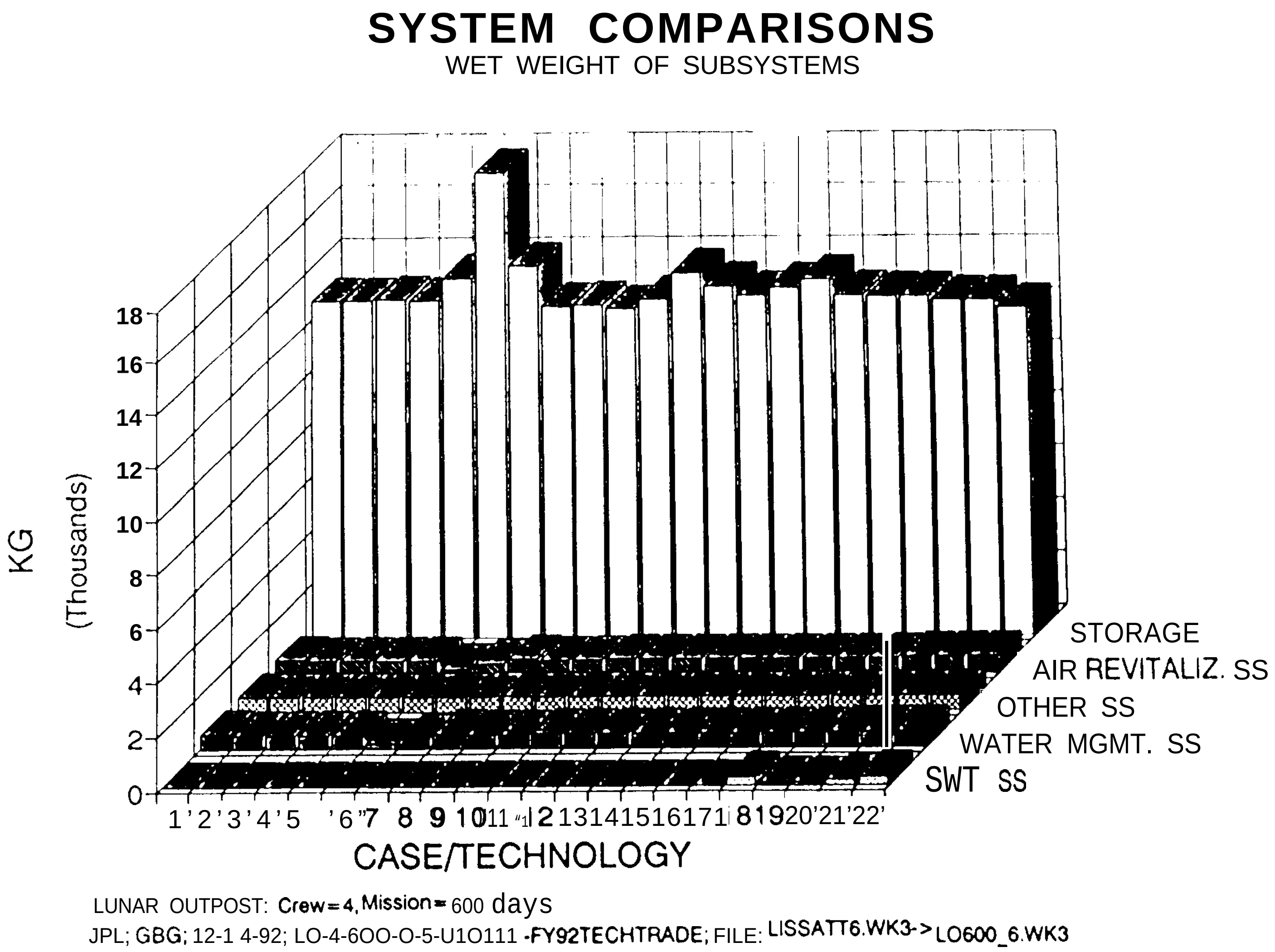


Figure 7-B Subsystem Weight Comparisons (600 day mission)

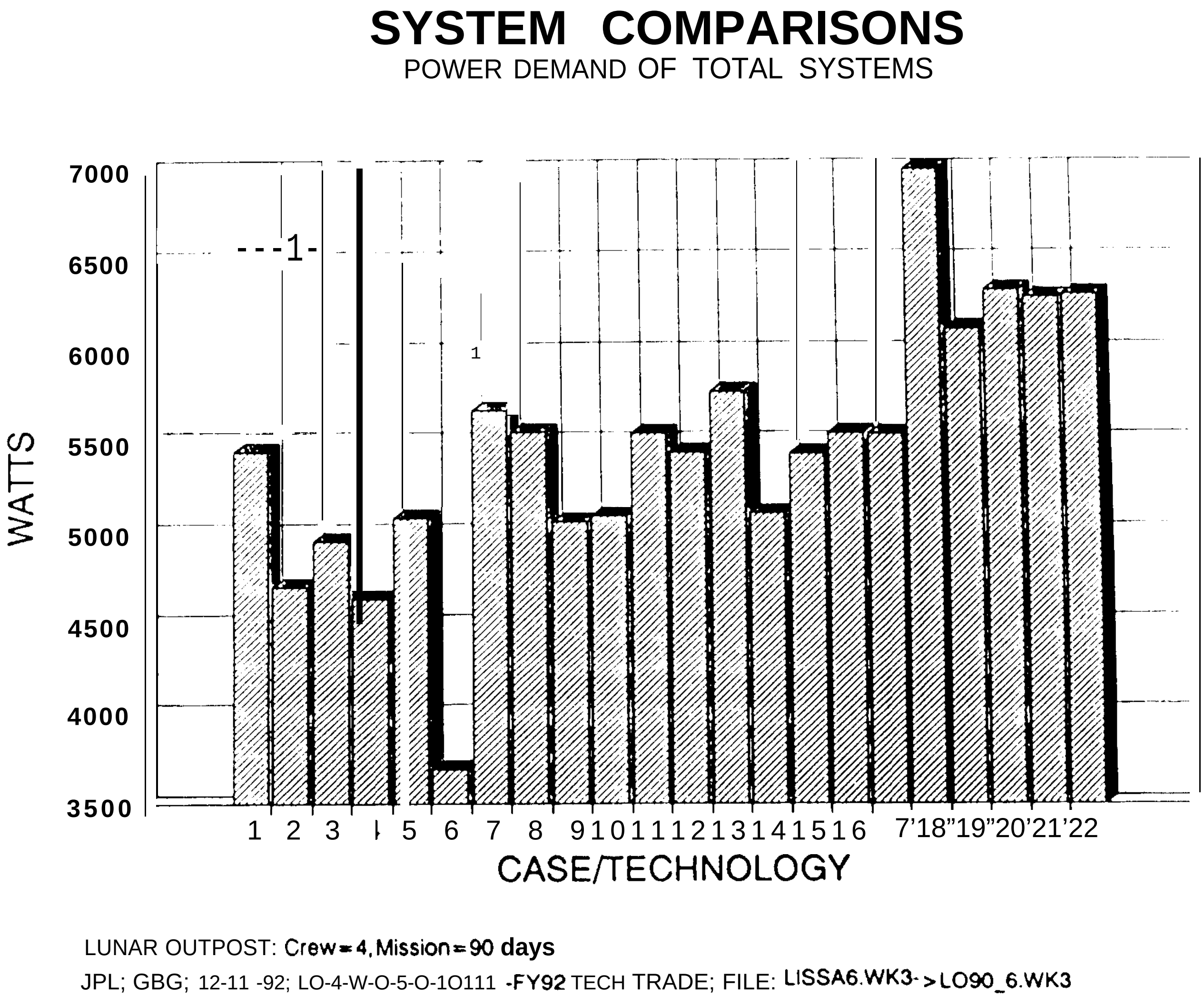


Figure 8-A System Power Comparisons (90 or 600 day mission)

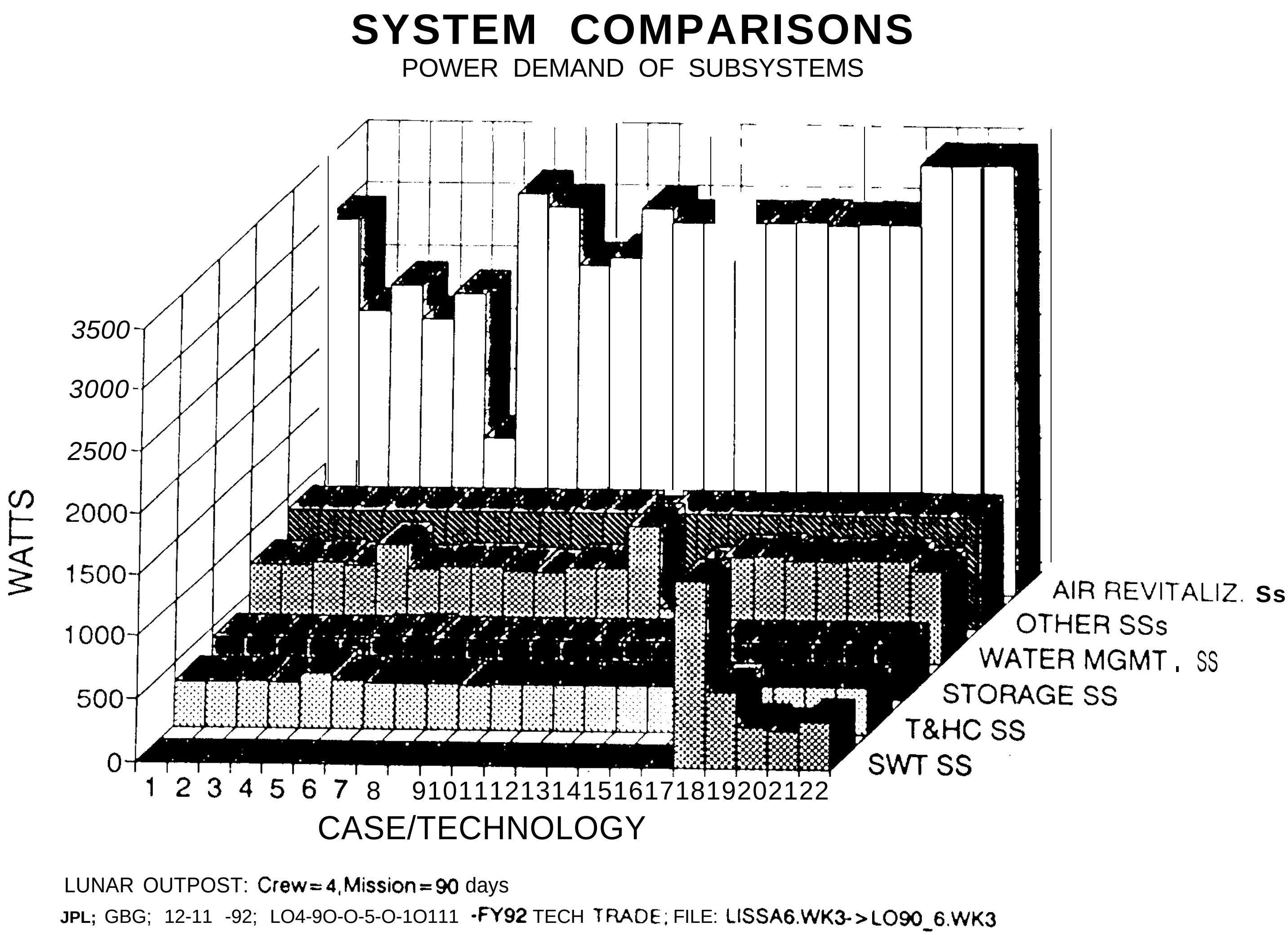


Figure 8-B Subsystem Power Comparisons (90 or 600 day mission)

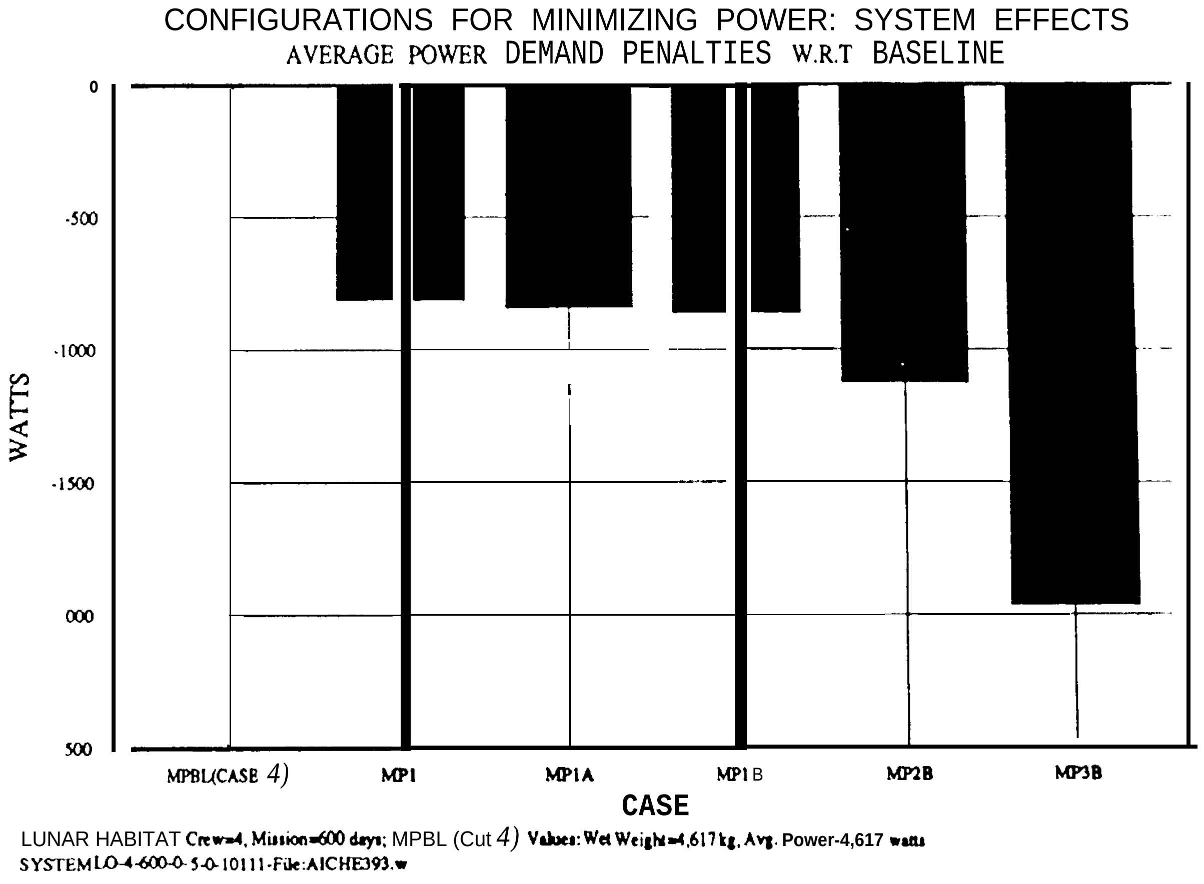


Figure 9-A Effects of Process Configurations to Minimize Power: System Power Penalties

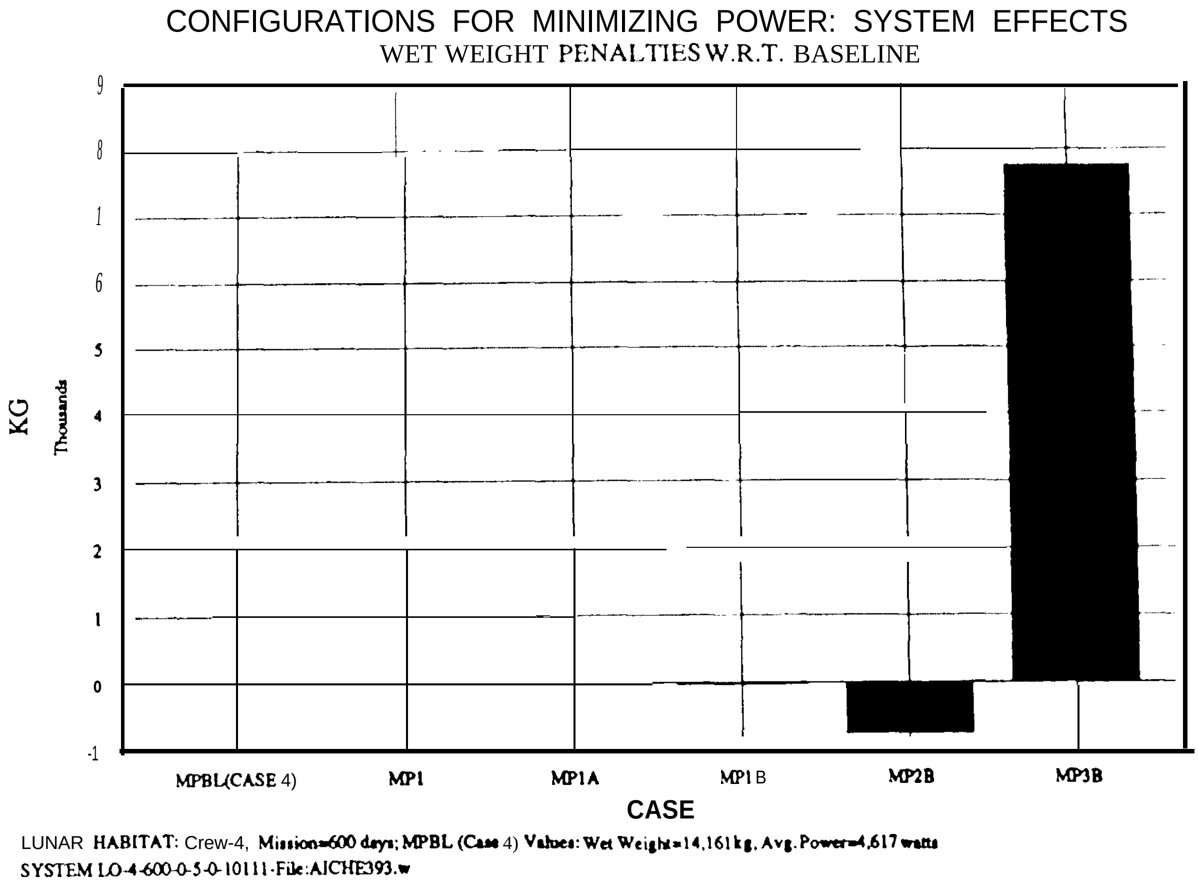
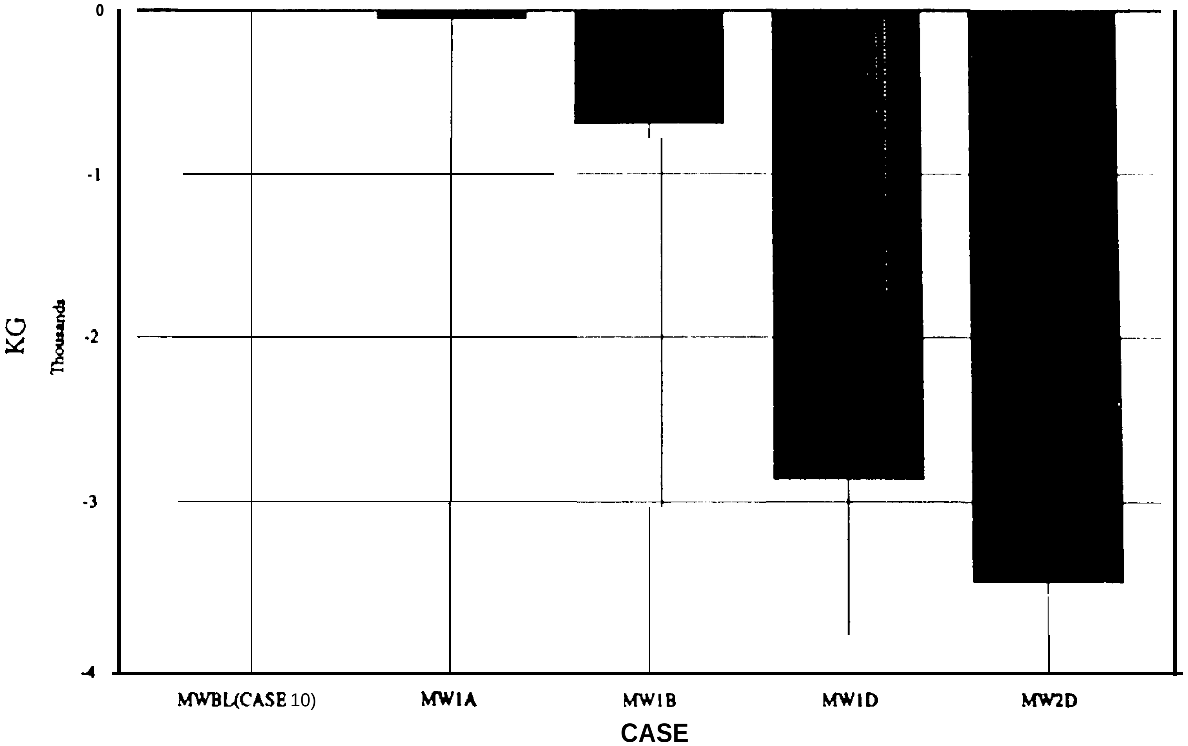


Figure 9-B Effects of Process Configurations to Minimize Power: System Wet Weight Penalties

CONFIGURATIONS FOR MINIMIZING WET WEIGHT: SYSTEM EFFECTS

WET WEIGHT PENALTIES W.R.T BASELINE



LUNAR HABITAT Crew=4, Mission=600 days; MWBL (Case 10) Values: Wet Weight=13,779 kg, Avg. Power=5,083 watts
SYSTEM LO-4-600-0-5-0-10111 - File:AICHE393.w

Figure 10-A Effects of Process Configurations to Minimize Weight:
System Wet Weight Penalties

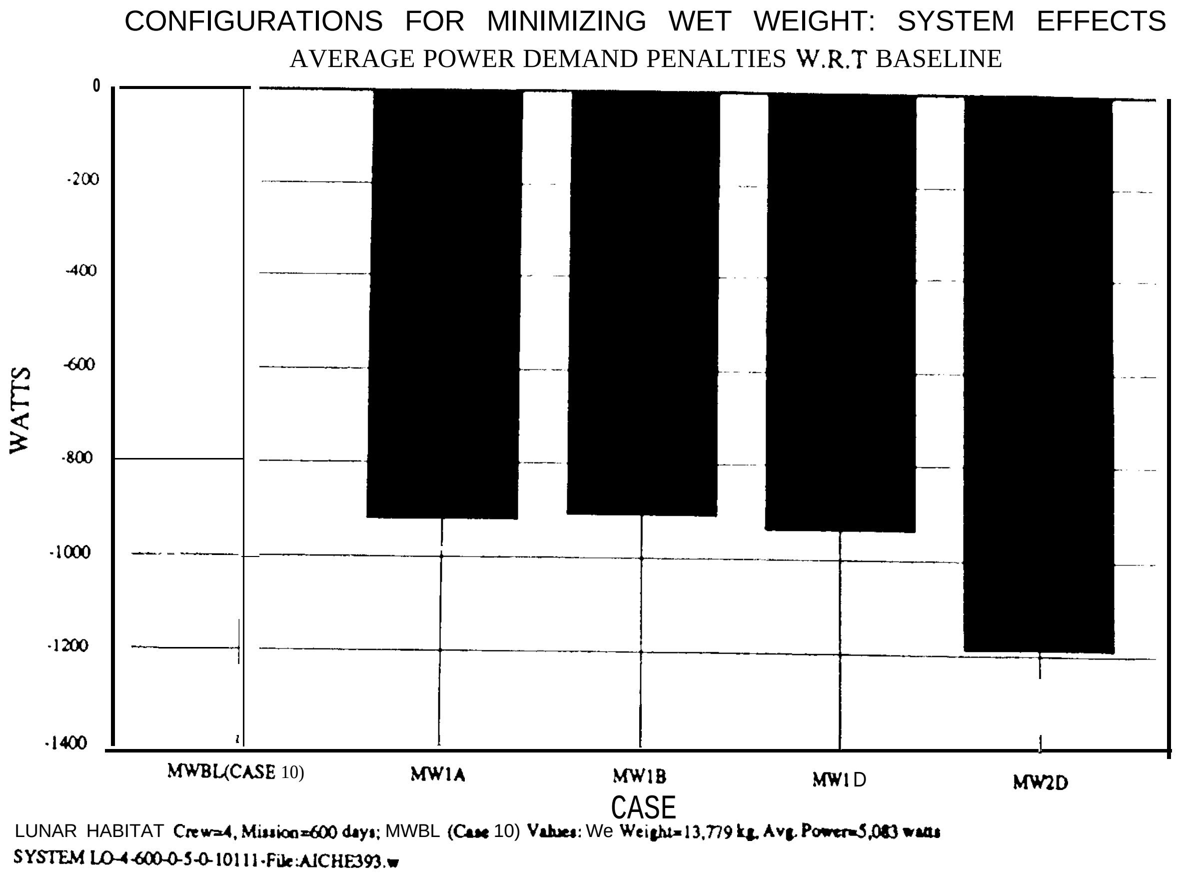


Figure 10-B Effects of Process Configurations to Minimize Weight: System Power Penalties